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In Two Sections
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Section II—March 1961 IE

PUBLICATION of this issue in two parts is an innovation introduced by the Publications Committee, as one step toward increased service to all members through the publications program. Its purpose is two-fold:

1. Publication of valuable Conference papers and discussion is speeded, for their earlier reference use to engineers.

2. Through the mass publication of a major portion of the 1960 Conference papers, space will be afforded in subsequent issues of IE for more material on the application aspects of lighting, practical discussions of current problems and techniques, and other material of particular and current value to the lighting practitioner, architect and consulting engineer.

In this part, designated as Section II of March IE, fourteen of the reference papers presented at the 1960 National Technical Conference are published, together with discussion and rebuttal. Nine other papers from the 1960 Conference program have already been published in the October 1960 through February 1961 issues. Twelve additional Conference papers, all of them having current interest for application engineers as well as future reference value, are scheduled for publication in subsequent issues of IE. Titles of the papers yet to be published are:

The Application of Sodium Lamps to Public Lighting—J. B. de Boer, N. V. Philips, Gloeilampenfabrieken, Eindhoven, Netherlands.

Light Transmitting Plastic Enclosure for Outdoor Lighting Equipment—Donald E. Husby and Melvin R. Anderson, Lighting Division, Westinghouse Electric Corp., Cleveland, Ohio.

Roadway Brightness and Illumination as Related to Luminaire Distributions—Arthur W. Fowle and Richard L. Kaercher, Holophane Co., Inc., Newark, Ohio.

Factors Affecting the Efficiency of Street Lighting Systems—Joseph C. Yaeger and Harold A. Van Dusen, Jr., Line Material Industries, South Milwaukee, Wis.

Progress in the Development and Application of Static Converters for High Frequency Fluorescent Lighting—W. H. Johnson, Lighting Division, Westinghouse Electric Corp., Cleveland, Ohio.

Measurement of Visual Information Cues—H. L. Logan and E. Berger, Holophane Co., Inc., New York, N. Y.

Aperture Lamps . . . Applied—S. C. Peek, Sylvania Lighting Products, Salem, Mass.

Electroluminescent Lamp Brightness Measurement—Robert W. Wollentin, Stanley R. Goldfarb and D. Clifford Bell, Westinghouse Electric Corp., Bloomfield, N. J.

Developments in Quartz Infrared Lamps—W. F. Hodge, General Electric Co., Cleveland, Ohio.

Air-Handling Troffers—Elden H. Witte and Benjamin S. Benson, Jr., Benjamin Division, Thomas Industries, Inc., Des Plaines, Ill.

Maintenance Factors for Interior Lighting—R. N. Edwards, Jr., Westinghouse Electric Corp., Cleveland, Ohio.

Fluorescent Lighting for the High-Speed Expressway—W. J. McCormick, Sylvania Electric (Canada) Ltd., Montreal, Que.

Research on

Street Lighting Glassware Breakage

By HAROLD A. VAN DUSEN, JR.

Several years ago, a small midwestern city installed new street lighting luminaires. Maintenance during the first year was negligible, but suddenly one June morning, there were many reports of broken glassware. The previous evening had been warm and humid, the typical calm before a storm. Shortly after dark a thunderstorm had struck with its strong wind and rain. Afterwards, a complete inspection of all the installed luminaires revealed that one-third of the new luminaires had cracked or broken glassware whereas a nearby installation of similar luminaires of a different make had suffered no breakage.

This story illustrates two items of significance in glassware breakage: (1) The weather condition described leads to an extreme degree of thermal shock to the luminaire glassware and (2) some luminaire designs suffer glassware breakage and others do not when subjected to similar environmental conditions. Much street lighting glassware breakage is due to thermal shock effects, while vandalism probably accounts for less glassware breakage than many people assume.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. Author: Line Material Industries, South Milwaukee, Wis.

Four years ago a research project was initiated for the purpose of gathering information that could be used to increase the reliability of glassware used in street lighting luminaires. One thing that soon became apparent was that there was no reliable test procedure available for determining the tendency of a luminaire design to suffer glassware breakage in service. Existing tests were usually variations of "water immersion" thermal shock tests which usually gave the same results for glassware designs that had a poor breakage performance record in service as for those with excellent records. One result of this investigation was the development of a test procedure which gives a good degree of correlation with service experience.

Information was obtained through consultation with glassware manufacturers, studies of the available literature, observation of numerous street lighting installations in service and the use of numerous laboratory tests and a special outdoor testing laboratory. The outdoor test laboratory, shown in Fig. 1, contained sixteen luminaires of various types operated at slightly over rated wattage to accentuate any breakage tendencies. The laboratory was instrumented to measure and re-

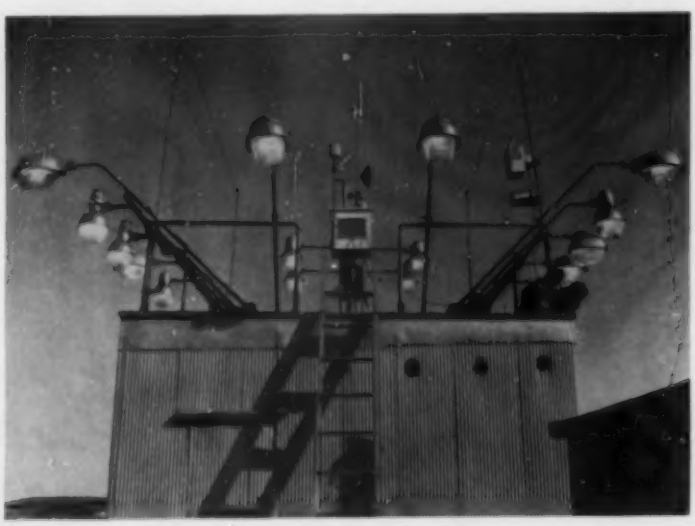

Figure 1. Outdoor test laboratory.

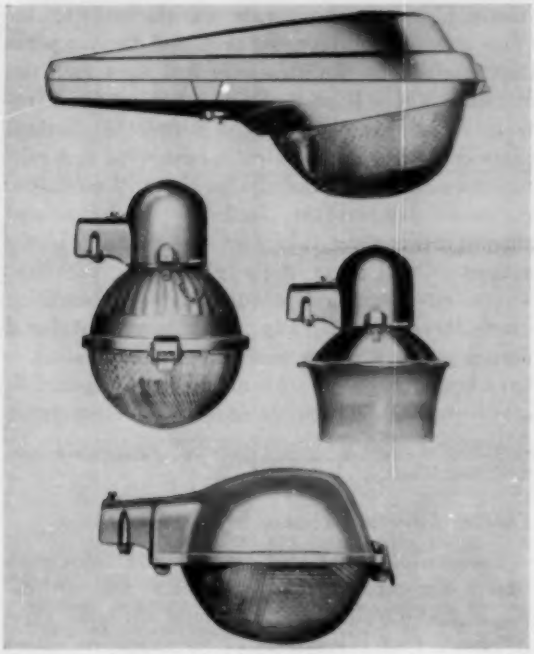

Figure 2. Some of the luminaires used in the study.

cord the effects of weather, such as ambient temperature, wind direction and velocity, rainfall rate, and relative sunlight intensity; and various luminaire temperatures. Fig. 2 illustrates some of the luminaire types studied. This test installation provided a means for determining many of the environmental conditions which contribute to glassware breakage.

Observations of installations in service included maintaining a close watch on a selected group of 14 lighting installations representing over 700 luminaires. Complete maintenance records were maintained for periods of one to two years so that actual breakage performance of three different luminaire-glassware designs could be compared. Breakage rates of these three designs were 31, 8 and 0.4 per cent per year. Of the breakages occurring in these installations, the majority were due to thermal shock or clamping strains and only about five per cent attributable to vandalism.

Characteristics of Glass

Glass offers many desirable features for street lighting usage; however, it has many unique characteristics, as compared with other engineering materials, which affect the design requirements of the luminaire-glassware combination. Glass is a true brittle material with extremely high inherent strength, but it does not have the capability of yielding to relieve localized concentrated stress and is, therefore, extremely notch sensitive. The fiber strength of glass is reported to be on the order of 2×10^6 pounds per square inch; however, the presence of any minute flaws sets up regions of high concentrated stress which effectively lowers the actual tensile strength.

Flaws, with rare exception, are always present on the surface of glass. They may be minute cracks, or even poor molecular bonds, and are usually limited to the surface. When glass is loaded in tension to an average value of 2000 to 20,000 pounds per square inch, the concentrated stresses at the roots of surface flaws reach values sufficiently high to cause them to grow. As a flaw, or crack, increases in size, the degree of stress concentration increases and growth continues to failure or until the stress is otherwise relieved.

Initial growth of flaws is actually rather slow, thus giving glass the pronounced stress-time characteristics shown in Fig. 3. As a crack grows, it often leaves wave-like markings similar to those shown in Fig. 4. Observation of these markings enables one to determine the initial origin of the break and the direction that the cracks followed as they grew in size. Breakage almost always originates at a surface and only when tensile stresses are present. The effective strength is extremely variable, even for identical pieces of glass, and therefore tests must include a large sampling for the results to be significant.

Strength varies little for different compositions of glass, although the stress generated by thermal effects will vary due to differences in coefficients of thermal expansion and elasticity. Therefore, thermal shock characteristics will vary for different compositions of glass. Tempered glass does have a higher effective mechanical strength and thus has a greater resistance to thermal shock breakage. It is not normally feasible, however, to

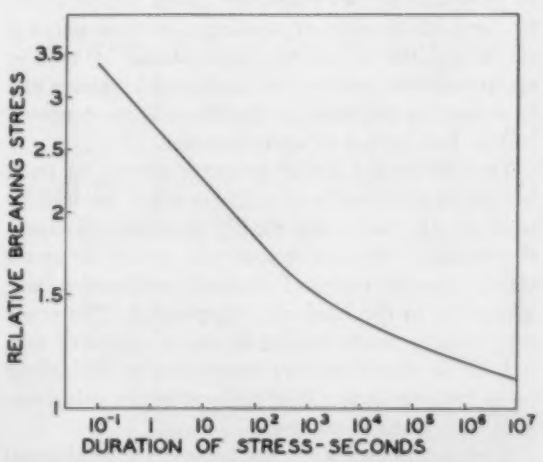

Figure 3. Approximate stress-time characteristic of glass.

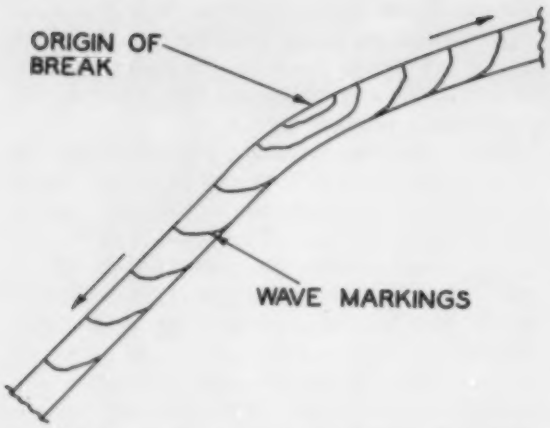

Figure 4. Illustration of wave-like markings often visible on broken sections of glassware. Direction of crack propagation is shown by arrows.

temper complex or prismatic shapes. Tempered, non-prismatic globes having a hemispherical shape have shown excellent performance.

Thermal shock breakage occurs when a surface of heated glass is suddenly cooled. The thermal contraction of the cooled surface is resisted by the adjacent warm interior portion of the glass, thus causing a tensile stress on the cooled surface. If the temperature differential is sufficiently great, the stress will be sufficient to cause failure. A measure of thermal shock is the peak temperature differential simultaneously occurring between the hottest internal area or surface and the adjacent cooled surface. The presence of extraneous tensile stresses on the cooled surface will lower the effective thermal stock resistance.

Breakage In Service

Most breakage in service appears to be caused by rain striking hot glassware. High winds, snow, etc., are all capable of causing a certain amount of thermal shock, but the shock caused by rain is apparently the most severe and most breakage can be traced to rainstorms. Breakage is most prevalent in late spring or early summer.

Very often the initial breakage occurring on a luminaire will consist of a single crack, an inch or so in length, that is not readily apparent on casual observation. Such a crack will generally grow slowly due to repeated thermal contraction and expansion as the luminaire is operated. The crack may require weeks before it causes complete failure. It is, therefore, not uncommon to find glassware breakage a month or more after the rainstorm that caused the breakage.

Ambient temperature has little effect on thermal shock breakage. Rainfall temperature is generally related to ambient temperature (rain tends to stabilize at wet bulb temperature) and the temperature attained by the glassware will vary with the ambient. There is no single weather condition responsible for breakage. The degree of thermal shock occurring is dependent on the wind and rain conditions prior to breakage, as this will affect the glassware temperature, and the rapidity and amount of cooling rain that is suddenly blown against critical areas of the glassware. The most severe environmental condition is a condition where there is practically no air movement for a period of an hour or more after the luminaires have been turned on (this allows the luminaire to attain the highest possible operating temperature) followed by a hard rain driven against the glass by a strong wind.

Factors Affecting Thermal Shock Breakage

The thermal shock breakage characteristics are a function not only of the glassware, but are dependent also on the luminaire and the lamp type. A measure of thermal shock breakage resistance for the glassware-luminaire combination is "Safe Operating Wattage." If the luminaire is operated at a wattage below this value, then negligible breakage (less than one per cent per year) is likely in service. Excessive breakage is likely if operated above this value.

Safe operating wattage is affected by:

(1) *Operating Temperature,* particularly glassware temperature in critical areas most exposed to rainfall. This is affected by lamp type and the luminaire thermal characteristics. The presence of dirt on the optics can have a very significant effect on the temperature by virtue of absorbing radiant energy from the lamp.

(2) *Thermal Shock Resistance.* Geometry of the glassware, type of glass, and mechanical clamping forces will affect this characteristic.

Mercury lamps cause a greater temperature rise in luminaires than do incandescent lamps. In general, it requires 1.8 watts from an incandescent lamp to heat glassware on a luminaire to the same temperature as one watt from a mercury lamp. Safe operating watts vary in the same manner with these lamp types. These unequal heating effects are due to the radiation spectrum of these lamps. Most of the input energy to an incandescent lamp is converted to near infrared radiation which is transmitted readily by glass and does not contribute to heating the luminaire. The inner arc tube in a mercury lamp operates at a temperature that generates a considerable amount of far infrared radiation which is not transmitted by the glass. This and some ultraviolet radiation are absorbed

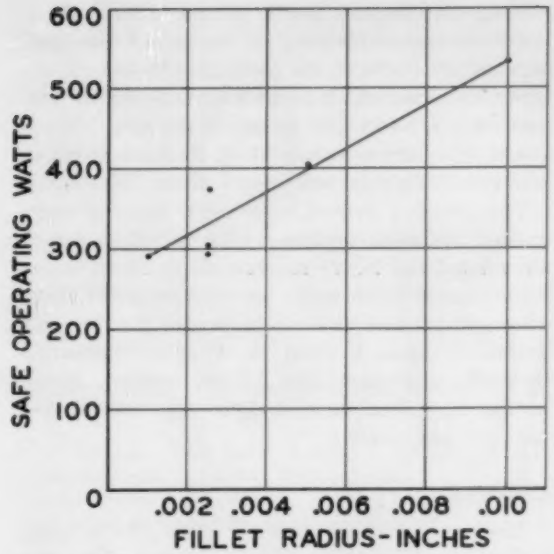

Figure 5. Effect of fillet radius at roots of prisms on a mercury luminaire refractor. Each point represents test data on an average of six specimens.

by the outer lamp envelope and the luminaire glassware, thus contributing to luminaire heating.

Some design considerations which influence the safe operating wattage are:

(1) Shield the critical flange area of the glassware as much as possible from rain and from high temperatures, as this area is generally less able to resist thermal shock stresses.

(2) The root fillets of external prisms cause stress concentrations if the radius at the root is extremely small. The effect of various root radii on one refractor design is shown in Fig. 5.

(3) High clamping forces between the glassware and its holder should be avoided. Allowance should be made for the difference in thermal expansion between the glass and metal.

The typical V-band construction is one exception where the use of high clamping pressure has generally proved satisfactory, although performance is often improved by using alternate types of construction which do not stress the glassware. The V-band tends to load the glass in compression which, ideally, should increase its resistance to breakage. In practice, however, the band does not bear against the glass uniformly and secondary tensile stresses usually develop, causing some net reduction in strength. Varying tension in the band has little effect on breakage characteristics.

Test Process

The classical method for determining the ability of glassware to resist thermal stress has been the use of immersion type thermal shock tests. In such tests, heated glassware is repeatedly immersed in cold water. The temperature differential between the initially heated glass and the water is gradually increased in successive tests until the specimen fractures. The temperature differential which causes 50 per cent of the specimens to break is the value of thermal shock resistance.

This type of test cools the surface of the glass very rapidly, thus building up high stresses at the surface. This causes failure before the internal portions have been able to assume a portion of the load. As a result, failure is not affected to any extent by the geometry of the specimen but is primarily a function of the glass composition, and the surface condition. The effect of sharp prism roots noted in Fig. 5 is not observed in this type of test.

Breakages observed in service do not have the characteristics of breakage observed in glassware specimens that have been subjected to an immersion test. Failures in service are characteristic of a slower rate of cooling.

A realistic thermal shock test for testing the glassware by itself would be desirable for quality control, but would be inadequate for determining the safe operating watts for the luminaire. The non-uniform heating pattern, the exposure of the glassware, and mounting strains, when installed on the luminaire, all affect the thermal strength.

Spray Test

A spray type of thermal shock test has been developed which gives results that correlate remarkably well with field experience. In this test, water spray traveling in a horizontal direction is suddenly applied to the side of a hot luminaire which has been energized for a sufficient time to reach full operating temperature. The test is cyclic. The

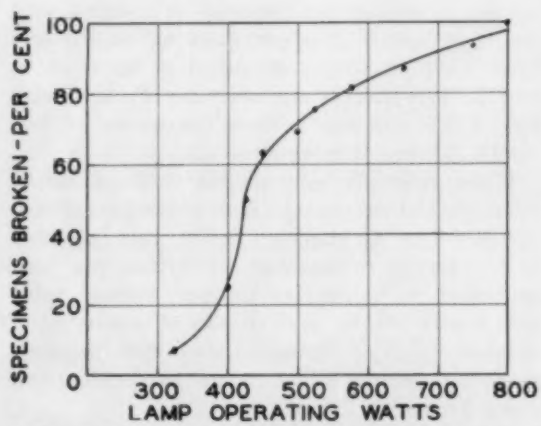

Figure 6. Typical breakage distribution pattern. Spray test on 16 glassware specimens. Mercury luminaire.

Figure 7. Spray test chamber.

luminaire is first operated at a low lamp wattage, spray is applied, and if the glassware has not cracked, the spray is turned off. The cycle is then repeated with the luminaire operating at a higher lamp wattage. The cycles are continued at progressively higher steps until breakage occurs. Generally six glassware specimens are tested and the wattage value at which 50 per cent of the specimens fail is the test result. An example of the typical spread in test results is shown in Fig. 6.

The test is conducted in a draft free room or chamber. The spray rate is maintained at 0.2 inch per minute measured in the vertical plane, and the water temperature is maintained at the same value as the ambient within the chamber. Fig. 7 is an illustration of the spray test chamber used.

Prior to testing, the glassware is abraided with crocus cloth on all flange surfaces and on any surfaces likely to become scratched or abraided in service. This tends to reproduce the effects of some service life and also reduces the scatter of test results between individual specimens.

While exact service conditions are not duplicated, the test represents a standardized set of conditions where the glassware cooling rate is related to the service environment. This test has been calibrated, by comparing the test wattage value with known service performance of a number of different types of luminaires (see Fig. 8). Safe operating wattage is determined by dividing test watts by 1.1.

This spray test produces breakage patterns similar to those observed in service. The cooling rate causing the thermal shock in this test is much lower than that obtained in an immersion type test. As an example, the cooling coefficient of the spray, as measured on a heated vertical copper surface, is .27 watts per square inch-degree Centigrade. The corresponding value observed in water is approximately 1.5 and in still air is .026.

This test has proved to be quite reliable when testing luminaire designs where the glassware is not subjectd to overly extreme clamping pressure. Rigid clamps which apply large forces to the glassware can produce failures in service that are not dependent upon thermal shock effects, although thermal shock may often be the trigger. Spray testing such luminaire designs does not always give reliable results.

Conclusion

Breakage of street lighting glassware is quite serious. Broken glassware is costly to replace, but more important it presents a serious safety hazard. The ability to determine the safe operating limitations should significantly reduce the incidence of such breakage due to the thermal shock. Because of the extreme strength variability of glass and the environmental extremes that can occur, it is unlikely that thermal breakage in service can be reduced to zero, although it can be reduced to an extremely low rate.

Luminaire designs in which the safe operating wattage is below the value desired can often be improved by:

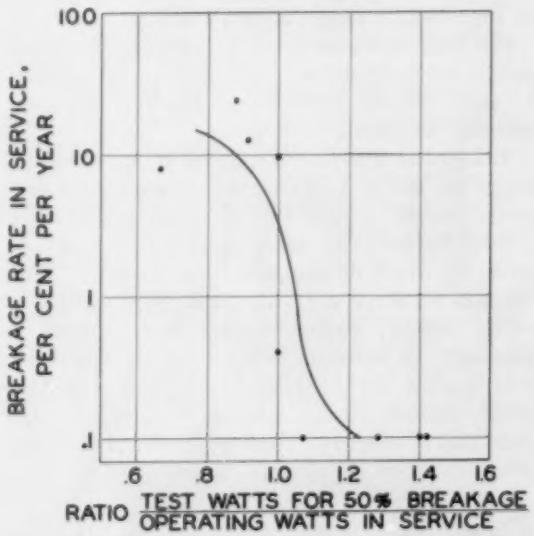

Figure 8. Comparison of service performance with spray test results. Each point represents the service record of 30 to 300 luminaires.

(1) Improving the cooling characteristics of the luminaire to reduce the glassware temperature.

(2) Improving heat distribution pattern on glassware so temperature variations are minimized.

(3) Reducing clamping forces on the glassware.

(4) Increasing fillet radii in prism roots and at projections, especially on the outer surfaces of the glassware.

(5) Changing to a more heat resistant type of glass when necessary. Borosilicate glass has a lower modulus of elasticity and coefficient of expansion and thus has a thermal shock resistance one and a half to two times greater than the commonly used lime glass. Lime glass, however, has somewhat better molding characteristics. The use of a more heat resistant glass is not a cure-all for breakage problems. Many of the other design factors have a greater influence on breakage.

Appendix—Specifications for Spray Testing Street Lighting Glassware

A. PURPOSE—This test is intended to indicate the maximum lamp size (in watts) that may safely be used in a particular luminaire without resulting in an excessive amount of glassware breakage in service.

B. GENERAL—This test tends to duplicate those field conditions most likely to result in glassware breakage, namely, heavy rainfall striking the refractor of a luminaire that has reached a high operating temperature. Although exact field conditions are not duplicated, this test represents a standardized set of conditions which are related to the field environment and produces similar results. In general, this test will cause breakage at lower wattage values than those observed in service. There is a relationship between test watts and safe operating watts in service.

C. PROCEDURE

(1) The test involves water spray striking the refractor at an angle of 90 degrees with the vertical and at a rate of 0.2 inch per minute as measured in the vertical plane. This test is related to extreme service conditions in which heavy rain is sometimes driven almost horizontally.

(2) *Test Cycle*—(a) The test consists of the following sequence: The luminaire is operated at a specific value of lamp wattage, and within a draft-free inclosure for a sufficient period of time to allow the luminaire and glassware to attain their maximum operating temperatures. A water spray is applied suddenly and maintained for at least five minutes while the lamp is still operating. During this period the glassware should be closely observed for the occurrence of breakage (Breakage is usually accompanied by an audible sound). The lamp is extinguished for a period of approximately 15 minutes while the spray is continued for a cooling period. If no breakage has occurred the spray is then stopped, the lamp re-energized and the heating and spray cycle repeated at a higher operating wattage. These cycles are continued at progressively higher wattages until breakage occurs.

(b) These test cycles are started at a wattage value below the minimum expected breakage and continuously increased in steps until breakage occurs. Typical wattage steps are 25 watts for luminaires rated at 200 to 500 watts.

D. DETAIL REQUIREMENTS

(1) *Test Chamber*—The luminaire must be operated within a room or chamber totally free from drafts. The chamber shown in Fig. A having one opening in the end will protect the luminaire from drafts if it is located within a room that is moderately draft free. The minimum size of the test chamber should be 75 cubic feet.

(2) *Water Spray*—(a) The spray should consist of individual droplets traveling in approximately parallel directions and obtained by breaking up a number of small jets of water on a screen. The water jets may be obtained from nozzles mounted on a horizontal pipe, spaced two to three inches apart and alternately directed 15 degrees vertically from each other. One or two such pipe and nozzle assemblies may be used as necessary to obtain a uniform spray pattern.

(b) The water pressure should be maintained by a separate pump at an adjustable constant pressure. Typical pressures involved are 5 to 15 psi.

(c) Water temperature should be maintained at the same temperature as the ambient within test chamber (±3C).

(d) The spray should be suddenly applied to the hot luminaire at full force. This is accomplished by interposing a shield between the spray jets and the screen while adjusting water pressure to a predetermined value which will result in the correct rate of precipitation.

(e) The rate of precipitation should be periodically measured directly in front of the refractor and the pressure therefore determined which will insure the correct rate. This rate shall be 0.2±0.05 inch per minute.

(f) Coarse adjustments to the spray rate can be made

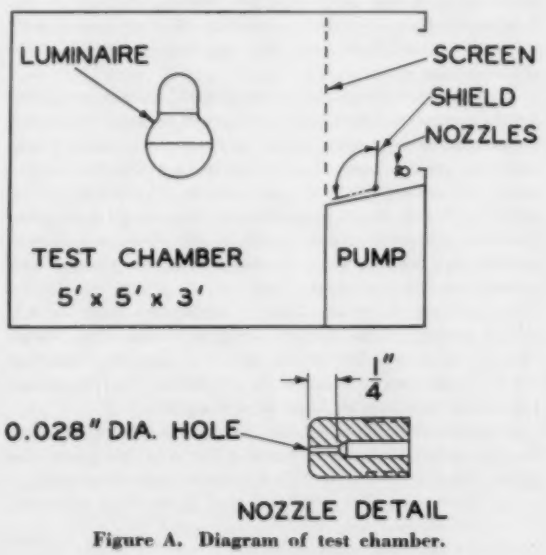

Figure A. Diagram of test chamber.

by varying the number of nozzles and varying the position of the luminaire. Sufficient nozzles should be used to provide a spray pattern that uniformly covers the entire unit.

(3) *Luminaire*—(a) The luminaire should be positioned such that the side of the glassware having the greatest tendency to break is positioned towards the spray. This is usually the hottest side and is generally determined by the location of the main beam.

(b) The luminaire should not be tilted out of its normal mounting position as this would change its heating pattern.

(4) *Preparation of Glassware*—(a) All surfaces of the glassware that may have a tendency to become scratched or abraided in service, such as flange surfaces and areas contacted by supporting members, should be abraided with emery cloth prior to testing so that effects of service life are included, and to reduce the scatter of test results. Abrasion should produce a visual dulling or scratching of the surface.

(b) The glassware should be clean. Any identification marks should be placed where they cannot intercept lamp radiation as this can change the heating characteristics.

(5) *Lamp*—(a) The luminaire should preferably be operated with the same type of lamp as used in service. The lamp type should be noted (Note: mercury lamps will heat luminaires to much higher temperatures than incandescent at similar wattages).

(b) For this test, mercury lamps can generally be satisfactorily operated through a range of 50 to 200 per cent rated wattage. Incandescent lamps should be limited to a range of 70 to 125 per cent of their rated watts.

(6) *Miscellaneous*—(a) The mechanical strength of glass varies considerably, thus resulting in a large spread of breakage wattage values. In order to obtain representative test results, a large number of samples must be used. In general it appears that sample quantities of less than six will give only approximate results.

(b) Test results should be presented as the watts required to break 50 per cent of the specimens.

DISCUSSION

WILLIAM F. CROSBY:* The test procedure employed here appears to be sound, although six specimens is a bare minimum sample. We note with approval the use of abraded samples. Undoubtedly the spray method, simulating heavy rainfall, is the correct manner in which to thermally shock luminaire refractors.

I should like to comment on the author's "Conclusions" as to means for obtaining higher safe operating wattages.

(1) No question about it. Any improvement in luminaire cooling characteristics will help.

(2) Our own somewhat limited spray test work, as well as theoretical considerations, tend to bear out the author's conclusion that even temperature distribution of the refractor surface increases thermal endurance. In this connection, the author's comment that the flange area of the glassware should be shielded as much as possible from high temperatures may be open to some question. If the flange area runs cool, it would be in constant tension, induced by expansion of the heated areas commonly existing immediately below the flange. I do agree that the flange area should be shielded from rain.

(3) Glassware mounting deserves most careful attention. As the author points out, V-band construction is generally satisfactory, as is a spun flange. However, cast metal rings, such as have been used on oval refractors, can be troublesome, especially if they are not smooth. The avoidance of point loading is of prime importance because glass is notch sensitive and sharp, rough points on cast rings can do real damage to glassware flanges, due to relative expansion and contraction and due to vibration.

In addition, if tightly clamped latches are used, considerable upward forces may be developed under the flange ends of an oval refractor balanced by downward bending forces in the central zone. Very substantial tensile stresses induced in this manner have been measured.

The current trend to substantially made refractor mountings, in which little or no bending force is exerted on the glass, appears to be favorable from this point of view.

(4) Increasing fillet radii is a step in the right direction. The avoidance of abnormally thick prismatic sections is also desirable, especially in a design which may be on the borderline thermally.

(5) The author observes that borosilicate glass has a thermal shock resistance one-and-one-half to two times greater than that of lime glass. If the thermal expansion of lime is taken as approximately 87×10^{-7} in/in/°C, this implies a borosilicate expansion in the region of 43.5 to 58 on the same scale. Actually, refractors are being made today in borosilicate glass of expansion 32.5, which represents a calculated thermal endurance increase of 2.7 times as compared to lime.

While some caution must be exercised in applying material properties to the final article, such an increase represents, in many cases, a real plus to the luminaire designer. It reduces the need to increase size, modify light distribution or limit lamp sizes for thermal reasons, or make other changes which may be difficult and expensive.

KURT FRANCK:* In view of the increased use of mercury lamps, it is especially timely that a paper has been written on this subject. As a major manufacturer of prismatic glass refractors for street lighting luminaires, we have been involved in several breakage complaints. It might be of interest to present the results of our experiences, particularly during the last five years.

Our records show a total of 68 complaints in the past five years, some of them serious and some not serious. Incidentally, all of the complaints were confined to mercury luminaires. With one or two exceptions, our investigations found excessively tight clamping pressures on the refractor flange. To the best of our knowledge, we can report that these abnormal breakages were all eliminated when the excessive clamping pressures were corrected. To cite an extreme example on an installation of 50 luminaires, 31 refractors were reported broken within a few days and it was simply a case where the workman evidently thought that all bolts and nuts should be made as tight as possible. It

*Corning Glass Works, Corning, N. Y.

*Holophane Co., Inc., Newark, Ohio.

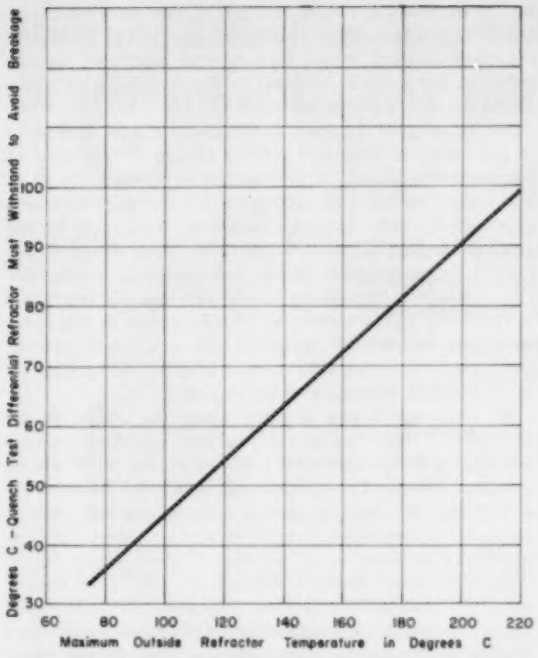

Figure B. Minimum refractor strength. Maximum operating outside temperature versus minimum outside quench test to rim (Franck Discussion).

should become obvious to the operating companies, therefore, that the first thing to look for, when abnormal breakage occurs, is excessive clamping pressure on the glassware. We wish to emphasize that this single factor is by far the most prevalent of all breakage causes.

The next most serious factor was found to be excessive dirt. The author has shown data which should help to emphasize the importance of proper maintenance. Of course, we have always assumed that operators would maintain equipment for the sake of obtaining maximum light output. However, the increased temperatures from dirt, which can often be critical, should give further emphasis to the importance of good maintenance. A prominent midwestern maintenance company recently reported that on a system-wide basis involving thousands of luminaires, the annual glassware breakage percentage was reduced from six to one per cent after regular cleaning schedules were instituted.

Secondary, but often significant factors found in our investigations were: (1) Chipped and bruised outside surfaces caused by mishandling; (2) Increased glass temperatures from higher wattage consumption of mercury lamps being operated beyond rated life.

Wherever reliable records have been kept on glassware breakage of the pressed prismatic designs, the annual replacement from all causes has been less than two per cent. Consequently, over the years, we have looked upon the two per cent annual replacement figure as a norm.

The testing procedure developed by the author uses a complete luminaire evaluation to obtain the "safe operating wattage" value. Our final approach to the testing of refractors is somewhat different. Immersion testing, as mentioned, has been long used in glassware strength testing. The most common type of test involves heating the entire glassware in hot water, then moving to total immersion in a cold water tank for the thermal shock. The difference in water temperatures is an index measure of the glassware strength at the time of breakage. However, the complete immersion test showed that almost all refractors break from the inside, which was contrary to field breakage analysis.

Cooling spray tests were tried and showed laboratory testing breakage similar to field breakage. However, a continuation of spray tests showed that it was difficult to always maintain a uniform refractor coverage. Therefore, we developed a different method which could be easily duplicated with consistent results. The outside quench test was found to be our best laboratory solution to refractor testing. This test uses hot and cold water tanks, as does the standard immersion test, but in giving the thermal shock treatment, only the outside surface is cooled to the rim (the entire area that could be hit by rain). Here, as in the full immersion test, the difference in water temperatures is an index of glassware strength at the time of breakage.

It was through the spray testing and, later, the outside quench testing that we were able to evaluate many outside glass surface problems. Only the outside refractor surface was found to be critical. This method of testing has been most useful in evaluating designs of the refractors as to prism roots, shape, and variations in glass thickness.

The correlation between our laboratory outside immersion quench tests and field operating conditions is shown in Fig. B. This curve shows the minimum quench test temperature differential a refractor must withstand to avoid breakage from thermal shock in the field. This is plotted against the maximum outside operating temperature of the glass surface. For example, a refractor with 100C or less maximum outside glass temperature will give satisfactory field service if it withstands a 45C quench test differential.

Although this test is quite useful in glassware design evaluation and manufacturing quality control, we recognize, and wish to emphasize, that it will not enable direct luminaire evaluation, as brought out in this paper. There appears to be a need for both types of testing.

A. M. BJONTEGARD:* A natural outgrowth of this paper might well be an industry standard on methods of testing for thermal shock resistance of glassware.

The factors listed as contributing to thermal breakage are consistent with our findings. The weighting of these factors may vary, depending upon the test method selected.

The effect of dirt accumulation on glassware can be a very significant factor. Measurements made indicate that the glassware temperature may increase 10C or more due to dirt. This not only makes the glassware more susceptible to breakage, but also reduces light output substantially.

I would like to have the author's comments on the data in Fig. 6. While the wattage rating of the lamp is not given, the percentage of specimens broken appears to be high. Has a comparable curve been made with samples which have not been abraded prior to the test? It would be desirable to isolate the effects of abrasion, whether deliberate or in-service. It is recognized that glass is very notch sensitive and that surface breaking, through careless handling, sharply reduces resistance to thermal shock and may promote breakage due to normal expansion and contraction.

In Fig. 8, the origin of the ratio of 1.1 (safe operating wattage to test wattage) is not fully apparent. Does this ratio compensate for dirt accumulation on components, such as glassware, which is encountered in service? Service wat-

*General Electric Co., Hendersonville, N. C.

tage of mercury lamps, for instance, may vary from rated wattage due to several factors. Among these are increases in wattage during life, lamp position, individual lamp variations (particularly when operated on regular ballasts) and the effect on wattage of the supply voltage or current when operated from non-regulator ballasts. The result of these elements is that service wattage is not well defined. For this reason, it is suggested that test wattage be related to *rated* wattage with a suitable factor which will compensate for service conditions.

H. A. VAN DUSEN JR.:* In reference to my statement that the flange area should be shielded from rain and high temperatures, Mr. Crosby questions the assertion that the flange area should be allowed to operate when it is cool. My statement was intended as a generalization and there are, admittedly, exceptions. As a general rule, the dynamic stress due to sudden chilling caused by rain is more severe than the static thermal stresses existing in the glassware during operation. The flange area is often poorly shielded from the chilling effects of rain, and even where it is not directly exposed to rain, such chilling may occur indirectly due to thermal conduction through the metal luminaire housing which may be in direct contact with the glass at this area. In such cases, there would be less tendency for a break to start in this critical flange area if its operating temperature were somewhat lower than that of areas of the glassware more able to withstand the higher stress. The temperature differences should never be allowed to be of any great magnitude, however. If this flange area is very well shielded from the chilling effects of rain, it might be preferable for it to operate at as high a temperature as adjacent exposed areas of the glassware.

In reference to the increase in thermal shock resistance of borosilicate *vs* lime glass, I agree that increases of more than two to one are possible. We have found increases in thermal shock strength as high as 2.15 with some types of borosilicate glassware available on the market.

Mr. Franck commented that in most of the cases of glassware breakage in his investigations, the luminaires involved were operated with mercury lamps. We have observed a considerable amount of breakage in service on incandescent as well as mercury luminaires, although mercury has represented the majority.

The presence of dirt on the optics can cause a large increase in temperature rise of the glassware. Unfortunately, I did not delve very deeply into this subject in the paper. The following is the result of a test evaluating this effect.

Light Output, Per Cent of Clean Luminaire	Per Cent Increase in Temperature Rise	
	Incandescent	Mercury
90	28	6
75	47	12
0	160	48

This table represents measured temperature rise on luminaire glassware which was made progressively more opaque by spray coating with black paint.

The quench test described by Mr. Franck is certainly an improvement over the conventional method of immersion testing. His curve relating quench test data to maximum outside refractor temperature should be a useful design guide. I would strongly recommend that this data not be used as a final determination of safe operating watts, however, since this is a test of only one of the many factors influencing breakage. A comparison of this curve with temperature data on several luminaires operated at their safe operating wattage shows variations in maximum outside refractor temperature in excess of plus or minus 20C from the values shown on the curve.

Mr. Bjontegard requested comments on Fig. 6. This curve is a summary of results of a spray test on 16 specimens of one luminaire design. A 400-watt mercury lamp was used, and in each specimen the wattage was deliberately increased progressively until breakage occurred. Reference to the curve shows that 425 watts input to the lamp caused 50 per cent of the specimens to break. Safe operating wattage for this luminaire is then determined by dividing this test result by 1.1. This yields a value of 386. Inasmuch as this luminaire was intended for operation with a 400-watt mercury lamp, the design was subsequently modified to increase its safe operating wattage to more than 400.

Mr. Bjontegard also inquired about the origin of the ratio of 1.1 used for determining safe operating wattage from spray test results. By referring to Fig. 8, it can be seen that a ratio of somewhat more than 1.0 is necessary if a high breakage rate in service is to be avoided, while a ratio of 1.07 was satisfactory in at least one case. This was arbitrarily increased to 1.1 to include a slight safety factor.

Safe operating watts determined by the above process actually represent the maximum lamp size that may be used safely. Effects of normal deviation from rated wattage and heating effects due to lamp variations, line voltage variations, and dirt accumulation are compensated for since these data are based on actual service performance of typical street lighting installations.

We have conducted a number of tests on non-abraded specimens and find some designs where the difference in performance between abraded and non-abraded specimens varies slightly, while with others the effect is very pronounced. Fig. C is a curve similar to Fig. 8 but based on non-abraded test specimens. It would be possible to evaluate safe operating wattage values of luminaire designs based on tests of non-abraded specimens; however, a ratio of 1.5 or 1.6 between test and operating watts should be used. The determination of the safe rating would be less precise due to the greater scatter in the comparison between test results and service performance.

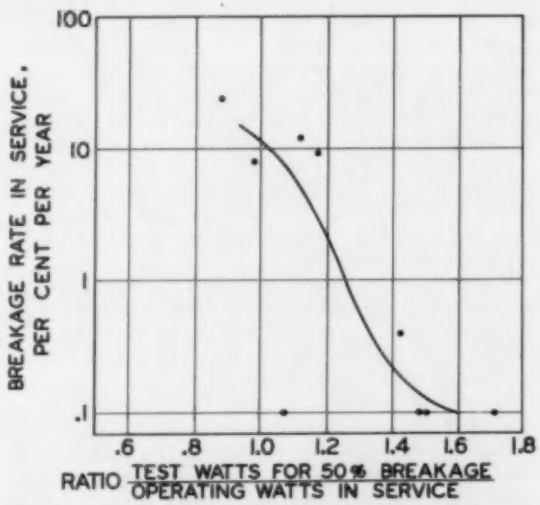

Figure C. Comparison of service performance with spray test results, non-abraded test specimens (Rebuttal).

*Author.

Mercury Ballast as an Integral Part Of the Street Lighting Luminaire

By R. W. HAGGSTROM

Selecting the proper integral-mounted ballast for the mercury street lighting luminaire need not be difficult if ballasting circuits and lamp characteristics are fully understood. This paper covers a complete description of the ballast design and application problems.

NOT SINCE 1934 when the first practical application of mercury lamps to street lighting was made has there been more interest than now, in lighting our streets and highways. This interest in street lighting grew steadily through the 1950's; one factor was the development of the highly efficient 400-watt EH1 type lamp that could be operated without a magnet in the horizontal position. During this same period the constant-wattage ballast was introduced and through improved circuitry and performance achieved wide acceptance in the late '50's, further stimulating mercury street lighting.

The introduction of the oxide electrode H33 type lamp in 1958 with its lower starting voltage and improved lumen maintenance further increased the interest in mercury lighting. The latest development, incorporation of the ballast within the luminaire, now provides the components for still wider application of mercury street lighting.

Inclusion of the ballast within the luminaire simplified the installation for the application engineer but introduced new problems for the ballast engineers and luminaire designers. In the past the ballast was designed to industry standards as a complete separate component, for direct application in the street lighting installation. The luminaire manufacturer had little concern with the ballast. The lighting engineer had a perplexing problem in choosing components for the lighting installation from a wide variety of both ballasts and luminaires. These had to be chosen so that the installation and operating costs were reasonable, and in addition provision had to be made for maintenance and suitable lighting performance.

The integral luminaire with its self-contained ballast simplifies installation problems associated with the remotely mounted ballast. These problems are now resolved by the joint engineering effort of the luminaire and ballast engineer, from the conception of the luminaire design to the complete luminaire with built-in ballast.

This paper is not intended to serve as a design manual; rather it will discuss the problems involved in placing the ballast in the luminaire. The factors to be discussed will touch upon the mechanical, electrical and thermal problems. The ballast circuitry and performance data provided will help the lighting engineer select the right ballast for the job.

An integral luminaire contains the light source, light control and all of the ballasting equipment in one enclosure. This highly developed package is made so that it can be installed simply by clamping to the support arm and connecting the line leads to a terminal board.

Fig. 1 illustrates one type of integral luminaire where the refractor assembly may be swung down to gain access to lamp, ballast and line leads. Other types of units have separate access covers for each major component but all provide easy accessibility to lamp, socket and ballasting components.

Fig. 2 is a close up of the luminaire with the refractor assembly down. Note that the ballast components are located between the reflector and the support arm so that the weight of the ballast is as close to the support arm as possible.

The ballast location in the same enclosure as the lamp produces an environmental thermal situation

Figure 1. Typical integral luminaire containing ballast components.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHOR: Jefferson Electric Co., Bellwood, Ill.

Figure 2. Refractor assembly swung down to gain access to lamp ballast and terminal assembly.

that is not encountered when the ballast is remotely mounted. Here the ballast insulating materials must be carefully selected for long ballast life under temperature conditions higher than previously encountered.

Ballast Insulating Systems

Basically, the users of electrical equipment are concerned only with the end performance, not with the means to reach this end. When components are brought together in a given luminaire, a vital responsibility exists between the ballast and fixture manufacturers. Ballasts for street lighting service must give long, trouble free, economical service; therefore special precautions are necessary in the selection of insulating materials to meet the requirements of the luminaire.

To determine the group or class of materials three major factors must be considered: first, the mechanical, thermal, chemical and electrical properties of the material; second, the processing conditions; and third, economics. These studies have to date favored Class F insulations for integral ballast core and coils. The size of a mercury ballast core and coil is dictated mainly by the maximum practical operating levels of flux density in the magnetic cores and by the current density in the copper wire. The small size and weight required can be acomplished only by designing to a higher temperature insulation level. Class F materials[1] are those capable of operation at 155C. This temperature limitation affords the best compromise between ballast performance, luminaire size, and total cost. This class of material provides a small light weight unit with excellent physical stability, good resistance to temperature and corrosive atmospheres with excellent dielectric qualities.

Capacitors

Ballasts can be designed for high ambient temperatures insofar as the core and coil is concerned (Class H) but capacitors for power factor correction and inductive-capacitive ballasting become critical at these higher temperatures. Capacitors presently available are limited to a maximum hot spot case temperature of 85C. For this reason special care must be used in their location and mounting to ensure that they will operate within this temperature limitation. The life of the dielectric in a capacitor is comparable to that found in transformeres if this temperature limitation is not exceeded. The temperature rise in a capacitor for these applications is high not because of its own dielectric losses, but because of its operation in a high ambient. The higher the ambient temperature, the quicker the dielectric reserve of insulation is exhausted. For long useful life the capacitor must be kept cool.

Ballast and Luminaire Considerations

The maximum ultimate temperature reached by the core and coil in the luminaire is due mainly to the heat generated by the lamp and transferred to the ballast coils by radiation, convection and conduction. The energy losses in the core and coil contribute only a small part to the total temperature.

To neutralize this thermal condition in luminaires, special precautions are necessary in positioning and mounting ballast components. A few of the important items are as follows:

(1) Intimate contact with cool portion of shell.
(2) Heat shields blocking radiant heat of lamp.
(3) Location as remote as practical from lamp.
(4) Heat conductors between the components and shell.
(5) Location not to be above lamp.

This evaluation of material and knowledge of heat transfer techniques have produced balanced insulating systems in the luminaires without sacrifice in operating efficiency.

Reactors

The reactor is the simplest, least expensive form of ballasting. Recent lamp design refinements[2, 3] have lowered the starting voltage requirements of a new type mercury lamp to a point that, now, reactors using 240 and higher line voltages for starting will give satisfactory outdoor service. The series reactor is small, light-weight and exhibits low losses, for these reasons it lends itself to use in the integral luminaire. The use of reactors, however, is linked directly to the power distribution system

TABLE I — Minimum Starting Temperatures for Mercury Lamps with Reactor Type Ballasting.

Lamp Type	Rated Line Voltage 240 Volts	277 Volts	480 Volts
100-Watt H4	+ 12 F	— 20 F	
175-Watt H22	— 10	— 20	
250-Watt H5	Zero	— 20	
400-Watt H1	+ 20	— 10	
400-Watt H33	— 20	— 20	
425-Watt H17			— 20 F
700-Watt H18			— 20
700-Watt H35			— 20
1000-Watt H15			— 20
1000-Watt H36			— 20

since this circuit voltage must be equal to or greater than the required open circuit voltage necessary for lamp starting and temperature involved. Since street lighting equipment must be suitable for —20F operation, the selection is somewhat limited. In Table I note that lamps rated 100 through 400 watts are suitable for use on 240- and 277-volt circuits, and the 425-, 700- and 1000-watt lamps are suitable for use on 480-volt circuits. Note that the minimum starting temperature is indicated for each line voltage. These values allow for some line drop and still give dependable starting. All of these values are based on currently available lamps and data from lamp manufacturers. In the near future, additional lamps with the improved oxide H33 type electrodes will be introduced. This will make possible —20F starting on 240 volts for lamps other than the present 400-watt H33.

Series reactors do have one serious disadvantage in that they respond to line voltage fluctuations and deliver low lamp watts when the line is low and high lamp watts when the line is high. For this reason, their use is limited to well regulated lines. Here a ± 5 per cent variation in line voltage will result in approximately ± 10 per cent variation in rated delivered lamp watts. Because of this, caution must be exercised in luminaire design to avoid the possibility of overheated lamps in luminaires providing insufficient heat dissipation when the line voltage is high.

The electrical circuit for reactors is as shown in Fig. 3a. The reactor contains a large amount of inductance causing an operating power factor of approximately 50 per cent lagging. A capacitor connected across the line as shown will correct the operating power factor to a minimum of 90 per cent lagging. Low power factor reactors (without capacitors) are less expensive and have the same lamp performance. These are suitable only where 50 per cent line power factor is permitted by local utilities.

Lamp current crest factors are excellent in series reactors as a result of the action of the air gap in the magnetic path. This impedance regulating air gap controls the inductance so that it remains almost constant with changes in flux density, thus reflecting a very low harmonic distortion into the current. As shown in Fig. 4, typical reactors have an almost constant lamp current crest factor over the ranges of operating line voltage and lamp arc voltage.

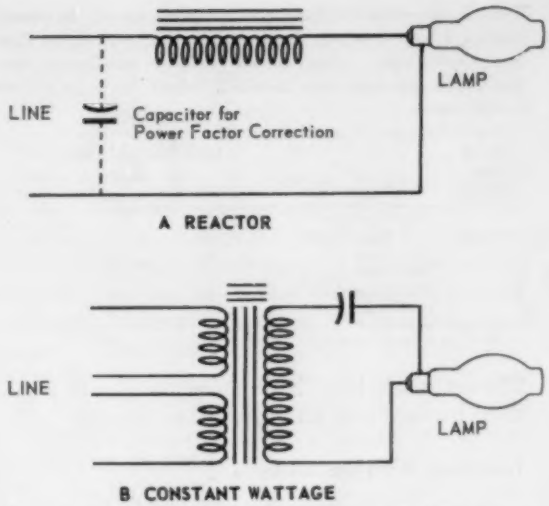

Figure 3. Schematic diagrams for typical ballasts used in integral luminaires.

High Reactance Ballasts

High reactance and auto-lag ballasts are not generally considered by fixture manufacturers for integral luminaires nor are they covered by this paper. These ballasts provide their secondary open circuit voltage by an auto-transformer winding which can be tapped for standard line voltages.

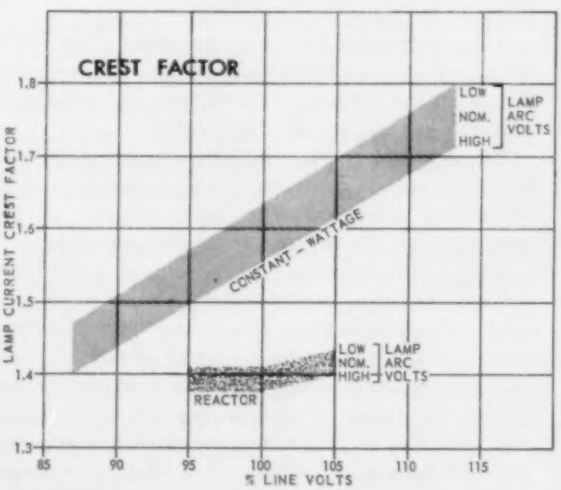

Figure 4. Comparison of crest factors for some typical reactors and constant-wattage ballasts operating lamps horizontally.

TABLE II — Line Current Characteristics of Reactors During Lamp Starting, Lamp Operating and Open Circuit Conditions. Figures are neither minimum nor maximum but represent nominal values for high power factor types.

Rated Line Voltage	Lamp Type	Line Current in Amperes		
		Starting	Operating	Open Circuit*
240-Volt	100-Watt H4	0.65	0.50	0.625
	175-Watt H32	1.5	.87	0.9
	250-Watt H5	2.1	1.2	1.3
	400-Watt H1, H33	3.2	2.0	2.15
480-Volt	700-Watt H18, H35	1.7	1.6	2.3
	1000-Watt H15, H36	3.6	2.4	2.3

*Following a lamp failure or interruption.

The net result is a ballast about the size of a constant wattage unit but without its benefits.

Constant Wattage Ballasts

Constant wattage ballasts are noted for controlling lamp watts to within two per cent despite line voltage fluctuations as high as 13 per cent. Besides this well known feature, they have many other corollary features such as:

1. No need for primary taps for line voltage variation or line regulation.
2. No line inrush current.
3. Low line starting current.
4. Low line-extinguishing voltage.
5. Line current reduction with lamp "short" or "open" condition.
6. Insensitivity to harmonics.[4]
7. Isolated lamp circuits.
8. Always high power factor.

Fig. 3b shows a typical circuit where lamp or secondary winding is electrically and physically separated from the primary winding. In this circuit the line voltage can never reach the lamp under any burn-out or dielectric failure, thereby averting lamp destruction.

The primary windings may be connected in series or in parallel allowing dual voltage range for a single ballast design. This reduces the need for stocking ballasts for each line rating.

The constant wattage ballast, because of its isolated circuitry, permits various schemes for grounding windings. The lamp circuit can be grounded with or without grounding the primary.

During the starting period, using conventional ballast, the lamp usually rectifies the starting current for approximately 120 cycles. This rectification in turn will produce several bursts of high line inrush currents each lasting approximately six cycles. The peak current during this period may rise from 5½ to 11½ times the rated line current depending on ballast design. In a constant wattage ballast the capacitor is in series with the lamp; therefore the direct current component produced by this rectification is blocked and cannot circulate through the ballast windings to saturate the core and cause high line inrush currents.

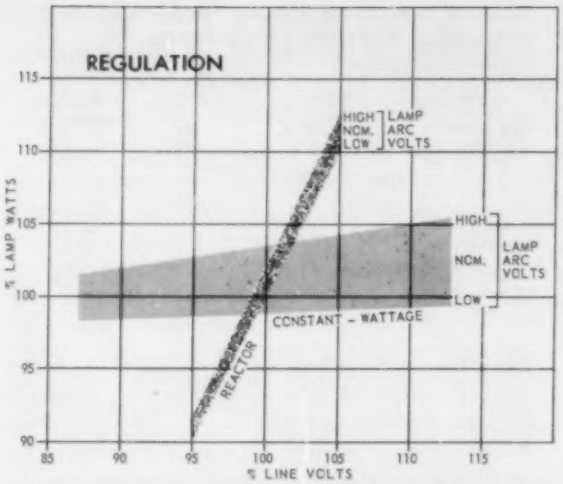

Figure 5. Comparison of horizontal lamp wattage regulation for typical reactors and constant-wattage ballasts.

Fig. 5 compares the regulation of the constant wattage ballast to that of the reactor. The lamp watts regulation changes more for variaton in lamp arc voltage in the constant-wattage type than in the reactor type. However, taking into account both watts regulation and arc volts variation, the constant-wattage type is much better. In fact, the line voltage for reactors, for comparable lamp performance, would have to be within —.6 per cent to +1.6 per cent.

Comparative values of line volt-ampere characteristics of constant-wattage ballasts are shown in Table III. Note that the greatest load on the line occurs during normal lamp operation. This means that the switching device can be rated for normal lamp operation. No derating is necessary.

Line Current Characteristics

In designing lighting installations, consideration must be given to determine the proper power facili-

TABLE III—Line Volt-Ampere* Characteristics of Constant-Wattage Ballasts During Lamp Starting, Lamp Operating and Open Circuit Conditions. Figures are neither minimum nor maximum but represent nominal values.

Lamp Type	Starting Volt-Amperes	Operating Volt-Amperes	Open Circuit** Volt-Amperes
100-Watt H4	85	127	52
175-Watt H32	71	210	120
250-Watt H5	92	288	186
400-Watt H1, H33	107	460	320
700-Watt H18, H35	115	780	290
1000-Watt H15, H36	360	1150	100

*To determine line current, divide volt-amperes by line voltage.
**Following a lamp failure or interruption.

ties, such as feeder conductor size and circuit breaker capacity. The starting, operating and open circuit characteristics of the ballast type will determine these values. In general, the constant-wattage ballast has its highest line current during normal lamp operation. For this reason it is to be preferred to reactors, where the highest line current exceeds the operating values, meaning additional copper costs for the installation. The reactors have their maximum line current under some other condition, depending on ballast design. In Table II and Table III the line current for each of the operating conditions is shown. These values must be observed in order that specified breakers or fuses will be adequate for the highest line current encountered.

Crest Factor

An earlier paper[5] discussed thoroughly the method of measuring current crest factor and its effect on lumen maintenance. Crest factors above a certain value cause a decrease in lumen maintenance and a corresponding increase in cost-of-light. Published data show no decrease in lumen maintenance for crest factors of 1.7 and below on horizontal burning lamps. A crest factor of 1.85 will drop the per cent mean lumens approximately 2½ percent. A crest factor of 2.0 will drop the per cent mean lumens down 10 per cent. Therefore, the knee of the curve is approximately 1.85 for the maximum economical crest factor. Any ballast-lamp operation at greater than 1.85 crest factor represents greater cost-of-light by either earlier lamp replacement or less light on the street.

The above crest factor analysis was made on horizontal burning 400-watt H1-type lamps. The 400-watt H33-type lamp, with its increased economic life rating, could possibly allow operation of higher crest factor ballasts without loss in per cent mean lumens. However, until the lamp manufacturers established the effect of crest factor on per cent mean lumens for H33 lamps, the ballast should be designed for the lowest possible cost-of-light. To accomplish this, the crest factor should not exceed 1.85 for the H1 or H33 lamps even when the lowest arc voltage lamp and the highest line voltage are applied to the ballast.

Fig. 4 is a graph of crest factor vs. line voltage. Plots for various lamp arc voltages on a typical constant-wattage and reactor ballast are shown. Note that the reactor has a much lower crest factor. The cost-of-light is inversely proportional to the mean lumens and since mean lumens are not appreciably affected when the crest factor is below 1.85, there is no difference in cost-of-light for either type. Ballasts having higher crest factors could be less costly but the resultant reduction in cost would not offset the rise in total cost-of-light, since the ballast cost is only a small part of the total lighting installation.

Ballast Application

A discussion of the integrated luminaire design would not be complete without touching on a few of the principles of ballast application. The previous discussions on reactors and constant-wattage ballasts covering their particular characteristics will assist in determining their use on any lighting system. The choice of a reactor is determined either by the voltage available on an existing circuit, or by planning and designing into a new system the regulation and line voltage variation compatible with reactors.

In new installations which are limited to mercury lighting, the line regulating feature of the constant-wattage ballast must not be overlooked, since substantial saving in copper can be realized. Here, in the case of a 100 to 130 line voltage range ballast, the power line can be adjusted to 125 volts ± 5 volts to operate the first ballast on the line. The application engineer can then specify the feeder wire size, and number of ballasts to be connected until the last ballast will operate at a nominal of 105 volts. This will retain a —5 volts for line variation. The 20-volt difference between the input voltage of 125 and the last ballast voltage of 105 can be utilized as line drop. The regulating feature of constant-wattage ballasts therefore permits the use of minimum wire sizes, maximum distance between lamps and maximum number of lamps. This concept of application can be utilized when ballasts specified indicate a primary voltage range. Ballasts of this type normally have their range stated on the nameplate or are guaranteed by the manufacturer to provide the minimum open circuit voltage and to operate lamps satisfactorily within this range.

In the case of reactors, lower than rated line voltage could mean delayed starting or inability to start at all, depending on the ambient temperature and type lamp being used.

In the near future, additional lamps similar to the improved oxide electrode H33 type lamps will be introduced. The new lamps for the 250-watt H5, 175-watt H22 and 100-watt H4 will, in all probability, have lower starting voltages than the present types. This will provide —20F starting on 240-volt circuits and increase the versatility of the simple reactor type ballast.

Conclusions

The integral street lighting luminaire makes possible simple-to-install lighting systems using mer-

cury lamps from 100-watt through 1000-watt. The reactor will provide a low cost lighting installation with excellent performance providing certain limitations are met. The constant-wattage ballast, with its many plus features, provides the application engineer with a ballasting means unparalleled by any other. The trend toward packaged light through the use of integral luminaires will lead to improved lighting on our streets and highways.

Acknowledgment

The author acknowledges his indebtedness to M. E. Robertson for his guidance, suggestions and criticisms in the preparation of this paper.

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DISCUSSION

J. A. MACCRACKEN:* The last sentence in the "Conclusions" should be underlined for emphasis. Truly the trend toward packaged or unitized luminaires will lead to a new day (or night) in street lighting. It is the outdoor version of the popular "pin-up" lamp.

This paper fills a very real need in the industry by translating the mysteries of the vapor lamp-ballast combination into everyday language. However, it is disappointing that the author stopped somewhat short of a full discussion of the cost-of-light relationships which he hinted at. For example, he suggests that small wire can be used in the supply conductors by taking advantage of the built-in regulation of the constant voltage ballast. But, at what price? Voltage drop means (at 100 pf particularly) watts loss, and watt losses cost money, even within the utility company itself. In fact, it may be economical (and indeed it often is) to use larger wire to save watts loss. Only a quantitative determination of the over-all factors involved will permit an accurate determination of the proper economic choice.

No mention is made of the fact that a constant-voltage ballast will, depending upon design, have several times the losses of an equivalent reactor ballast—and again these losses cost money. Where street lighting is on peak (as in most of the North) these losses add directly to system demand, and even when off-peak use up kilowatt hours.

It should be noted that in general since the advent of television, voltage regulation on secondary supply wires has received a great deal of attention from distribution engineers. Experience with a fairly large number of reactor ballasts in New England has shown no trouble whatever which could be attributed to fluctuation of secondary voltage. While the evidence is entirely negative it tends, on practical grounds, to discount the need for such extremely close regulation with the mercury lamp as the constant-voltage ballast is designed to provide. It would therefore seem that the choice of ballast should rest upon the over-all factors affecting the ultimate cost of light and not only upon the parameters of the ballast.

*New England Electric System, Boston, Mass.

W. M. WALDBAUER:* In general, I would agree with the considerations involved in the selection of insulating systems. The choice of Class F may be applicable when dealing with a single luminaire-ballast combination. It should be noted, however, that most luminaire designs are incorporating more than one wattage class of equipment. At present, it is common practice for a particular outer enclosure to incorporate combinations ranging from 175 to 400 watts. Some designs have traversed the range from 175 to 1000 watts in substantially the same enclosure. Under these conditions, insulation systems ranging from Class A to Class H may be appropriate.

The author has dealt briefly with the interrelationships of ballast, lamp, and optical system with particular emphasis on heat transfer characteristics, ballast losses and wattage control. Herein lies the major design problem associated with "internal ballast luminaires" which emphasizes the desirability of single design responsibility over all components.

The data in Fig. 5 of the paper are substantially in agreement with those presented earlier on the H-33 lamp.[1] However, it is felt that the term "constant wattage" is a misnomer. A device whose output wattage ranged from 98 to 106 per cent would more correctly be recognized as a regulated output device.

From an application standpoint, the "regulated output" design, due to the features mentioned by the author, is becoming very popular. It is especially applicable to old distribution systems where overloaded equipment and conductors result in poor regulation and/or where the voltage at the utilization point is unknown. The study of distribution system regulation could thus be minimized. On new systems, the author has proposed the use of "regulated output" ballasts together with reduction in conductor sizes to take full advantage of allowable line voltage range. Here the use of a more expensive ballast plus additional line losses plus additional ballast losses must be compared to the use of a simpler, less expensive ballast, and an adequate distribution system. If copper costs are the major consideration, then surely the use of internal ballasts of the series ILH type must also be considered.

While the "internal ballast luminaire" has simplified the application engineer's approach to system design, the choice of ballast type still rests on the economics of the particular problem at hand.

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*Westinghouse Electric Corp., Cleveland, Ohio.

D. A. TOENJES:** The author has presented a useful guide to selection of ballasts for mercury lamp luminaires of the integral ballast type. More than its title would lead us to expect, a major part of the paper is devoted to the choice of various characteristics of the ballast, other than its physical coordination with the luminaire. I would welcome some further discussion of comparative costs and savings that depend upon the choice of ballast location. Would the author care to offer some estimate as to the saving in installation and maintenance costs (expressed either in dollars or man-hours) to be gained by use of an integral ballast design in the luminaire hood, as compared with separate installation at the top or base of the poles?

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In the section on "Reactors" the possible use of low-power-factor reactors without capacitors is mentioned. Would there be another possibility, namely, the use of low-pf reactors and a combined pf correction at the distribution transformer? As compared with the high-pf system, this would lead to more line losses or require larger conductor size in the secondary system, but would permit the use of fewer capacitors of larger size, located away from the luminaires. Would this offer any cost saving? If it appears impractical due to combined use of the multiple circuits for purposes other than street lighting, could such capacitors be switched into the circuit by the same photoelectric control that turns on one of the luminaires?

No mention is made of series circuits for street lighting with mercury lamps. Does the author predict that it will always be necessary to use externally-mounted ballasts with series circuits, because of limits on insulation and spacing imposed by the higher voltages? In Figs. 4 and 5, the curves are broadened by variations in lamp voltage. Does the range from "high" to "low" on the figures represent a range of lamp operating voltage from 120 to 150 volts for the 400-watt lamps, for example? This same question might be stated in another way: What percentage of total available lamp product is represented by the variations shown?

In Tables II and III, the lower starting current is shown as applying to the constant-wattage ballast design. While this has the advantages mentioned in circuit loading, it also tends to require a longer warm-up time for the lamps when they are first turned on—even when the lamp and circuit characteristics lie within acceptable limits. Would this not lead us to expect that a perhaps hypothetical ballast design, in which the starting volt-amperes were equal to the operating volt-amperes, would be the most desirable compromise between circuit loading and warm-up characteristics?

In the section on "Ballast Application" the author suggests that selection of feeder wire size be based upon distances and number of luminaires to be installed, to permit the minimum wire size that will still operate the circuit within an acceptable line-voltage variation. Does this appear to be, generally, the most economical choice? It offers some saving in conductor costs, but also leads to higher line loss than if larger conductor size were used.

It is encouraging to see the author's attention to lamp current crest factor and its effect on lamp performance. Since the preparation of the paper, we have completed tests on the effect of lamp current crest factor upon performance of the new oxide-electrode lamps. The results of these tests showed that lumen maintenance of oxide-electrode mercury lamps is less affected by higher current crest factors. Therefore, we have recommended to the ASA Mercury Lamp Subcommittee that a current crest factor limit of 2.0 (with center voltage lamps measured in the vertical position) be established for the oxide-electrode mercury lamps.

A. D. HARRINGTON:* This paper presents a rather comprehensive discussion of various types of ballasts and their applications. However, it does not delve deeply in the specific problem of integral mounting within the luminaire.

We question the allowable case temperature of 85C for the capacitors. A limit of 75C is a more conservative temperature for a satisfactory life expectancy.

We also question the range of lamp watts shown in Fig. 5 for the constant-wattage ballast. Do these data cover the full range of lamp voltage variation of 120 to 150 volts?

Regarding the author's comment on "Line Current Considerations," we question whether a utility would actually increase system copper costs to allow for short term excess starting or open circuit primary currents. This would not be a realistic consideration. On the other hand, fusing and breaker allowances are a more significant problem. Furthermore, the staggered starts obtained with the popular unit type photoelectric control system would minimize the cumulative effect of line drop affecting starting.

R. W. HAGGSTROM:* The discussers have raised several interesting points relating to cost-of-light and ballast choice. A cost study on this subject and also on the comparison of installations using integral luminaires compared to remotely-mounted ballasts, would be of considerable interest to application engineers. This topic alone has sufficient depth in subject matter to offer an engineer an opportunity to study the possibilities and report in a paper.

Mr. MacCracken's comments indicate the experience he has had using reactors. I certainly agree with him that the reactor ballast has many features which make it desirable as a lighting tool from a cost viewpoint. However, the limitations must be reviewed during the system design stages so that, in actual service, proper line maintenance is observed.

Mr. Waldbauer's comments included substantiation of the test work included in the paper but did not agree on the term "constant-wattage." The lack of accurate definitions for terms used in outdoor lighting has, at times, led to a few misunderstandings. I have defined "constant-wattage" as a type ballast that maintains the wattage to a reference lamp to within ± 2 per cent when the line voltage is varied ± 13 per cent.

One of Mr. Toenjes' questions concerns the use of low power factor reactors in systems with a central point selected for locating power factor correction capacitors. Such a scheme does offer possibilities. The introduction of the oxide electrodes into all lamp sizes provides reliable cold weather starting; reactors mounted in standard NEMA heads offer excellent lamp control at low cost. If such a system could be correlated with a central capacitor control through the use of proper switching techniques, I would expect excellent lighting performance. Series lighting transformers were not included within the scope of the paper. However, series mercury lighting transformers are being installed in luminaires with excellent results. Perhaps a future paper will cover this subject more thoroughly.

Both Mr. Toenjes and Mr. Harrington questioned the ranges of lamp arc voltages shown in Figs. 4 and 5. The ranges of "high" to "low" represent a lamp operating voltage range of 120 to 150 volts for the 400-watt lamp. The terms "low," "nominal," and "high" include all mercury lamp sizes regardless of rated nominal voltage.

Mr. Toenjes, in referring to Tables II and III, indicated longer warm-up time for constant-wattage because of the lower starting current. This assumption is incorrect. Tables II and III refer to line current, not lamp current. The lamp starting current of all constant-wattage or regulator type ballasts is well above the minimum rms values as required in the present or proposed ASA mercury lamp specifications. The warm-up time for lamps operated from constant-wattage or regulator type ballasts is no longer than that for any other ballast. The "hypothetical ballast," in which starting line volt-amperes are equal to line operating volt-amperes is available in non-constant-wattage designs.

The recent announcement by lamp manufacturers introducing oxide electrodes into the smaller size lamps makes Table I incomplete. With the introduction of the 100-watt H38, 175-watt H39 and the 250-watt H37, there is now a full range of mercury lamps, from 100 watts through 1000 watts, which will start and operate at —20F utilizing reactors.

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Derivation of Ballast-Lumen Ratio

By J. C. HEFFERNAN

Measurement of ballast per cent light output for extra-high-output lamps has created serious problems for testing laboratories because of the extreme sensitivity of these lamps to air currents and temperature. Various short-cut methods have been devised by the laboratories, but the high costs involved make these systems questionable. Per cent light output can be computed from a basic formula using two main relationships: (1) luminous efficacy as a function of electron density or lamp current and (2) amount of light generated by a given lamp is proportional to power input, lamp current remaining constant.

DUE TO THE increasing use of heavily-loaded lamps, accurate lumen output data on the ballast-lamp combination is being required by many agencies that have designed installations around the published ratings of these lamps. The extreme sensitivity of these lamps to air currents and temperature makes it difficult for the agencies to gather the necessary data. Also, the protracted stabilization period required by the lamps to reach proper operating conditions has aggravated this condition.

In order to measure these lamps, the testing laboratories have devised short-cut methods to speed stabilization and maintain lamps at a certain condition for protracted periods. This is done by various water-cooling set-ups when the lamp mercury temperature and pressure are held at a constant value by immersion or contact with water at a specific temperature. Another method has been proposed by W. W. Brooks.[1]

There are, however, definite limitations to these methods, *i.e.*, the invariability of mercury temperature with lamp current, which preclude their immediate acceptance. Also, the cost of this equipment and the steps necessary to maintain it make it too expensive for those laboratories where only 10 or 20 measurements may be made each year.

This paper will show relationships between the luminous efficacy of a lamp and its current, and the light output of a lamp and its power input. These ratios can be used to determine the lumen output of a heavily-loaded lamp on a specific commercial ballast.

The use of this technique is not limited to the 1.5-ampere lamps, but is applicable to all types. The 1.5-ampere lamp is used for this work because of the special problems inherent in the testing of these types.

Lamp Volt-Ampere Relationships

Lamp voltage is nearly independent of lamp current. The number of electrons moving in the lamp (electron density) is a function of the current furnished by the ballast. Any increase in electron density means that excited atoms in the lamp will have less time to return to ground state (by radiating ultraviolet energy) before being hit by another electron and brought into a higher level of excitation or even ionized. This increased ionization causes more charged particles, etc., thereby lowering the lamp voltage necessary to maintain the discharge. However, when these atoms are raised to their higher excited levels, the ultraviolet radiation associated with the return to ground state does not occur. This loss in ultraviolet radiation causes a decrease in the luminous efficacy of the lamp.[2]

Lamp Wattage and Light Output Relationship

Total lamp wattage supplied by a ballast is proportional to the area under the wattage curve. Examination of the wattage curve and the light output curve of a lamp shows that they are very similar in shape and phase.[3] The light output can thus be tied closely to the lamp wattage. Lamp wattage is controlled by the voltage and current wave forms.

The current wave form supplied by a ballast determines, to a great extent, the wattage supplied to a lamp—the higher the peaks of current, the lower the lamp wattage. These high current peaks are believed due to core saturation and harmonics, since they become more pronounced as the ballast input voltage is raised.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHOR: Sylvania Electric Products Inc., Danvers, Mass. Accepted by the Papers Committee as a Transaction of the IES.

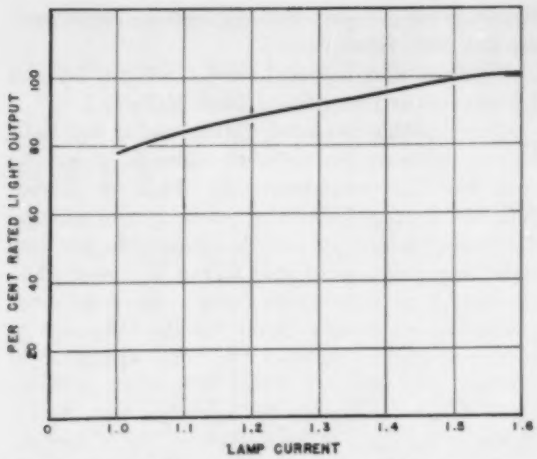

Figure 1. Variation in light output with lamp current on a transformer linear reactor circuit, separately heated cathodes, one 96-inch extra-high-output lamp.

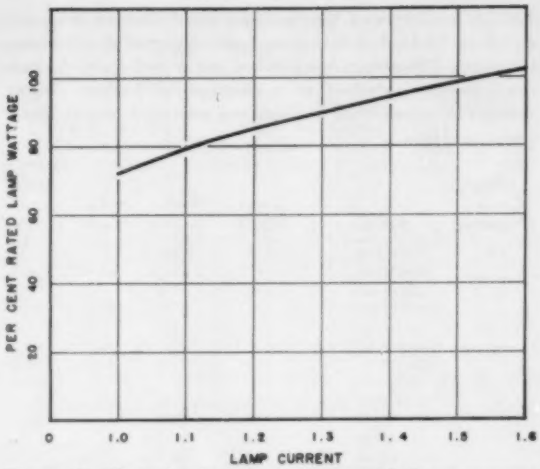

Figure 2. Variation in lamp wattage with lamp current on transformer reactor circuit, separately heated cathodes, cathode wattage not included, one 96" EHO lamp.

The voltage wave forms of a lamp are determined mainly by the lamp shape, size, fill and pressure. As noted above, lamp voltage is influenced by current density.

Lamp Power Factor

Power factor is generally defined as the cosine of the angle between voltage and current in a power load. Since the current and voltage in a fluorescent lamp are considered in phase, the variation between volt-ampere values and wattage should be called form factor. The form factor of the 1.5-ampere lamp on most of the present-day commercial ballasts is between .73 and .78. On a transformer linear reactor ballast, the form factor is approximately .84.

Variation of Light Output With Loading

As noted previously, the luminous efficacy of a lamp will vary with electron density for values below limiting current densities.[2] As the lamp current is reduced below its rated value, the luminous efficacy will increase. A series of measurements were made on the 96-inch, 1.5-ampere lamp to see the effect on this type lamp. These were made in an open-type luminaire with a transformer and linear reactor circuit used for ballasting. Lamp current was varied between 1.0 and 1.6 amperes. Readings of footcandles, lamp wattage and current were taken. The results are plotted in Figs. 1 and 2. Using these data, a set of lumens per watt values were computed for each current.

By dividing the lumens per watt at each current by the lumens per watt at rated current, a factor called "Efficacy Factor," K, is found. This value is plotted on Figure 3. With this efficacy factor known for a specific lamp current, the per cent light output ratio between a commercial ballast and a reference ballast should be directly proportional to lamp wattage on the two ballasts multiplied by the efficacy factor to correct for the lamp current. This is developed further in the following paragraphs.

Light Output on Commercial Ballasts At Various Currents

To check the validity of the statement that the light output is proportional to lamp wattage at a given lamp current, a series of tests were made. A

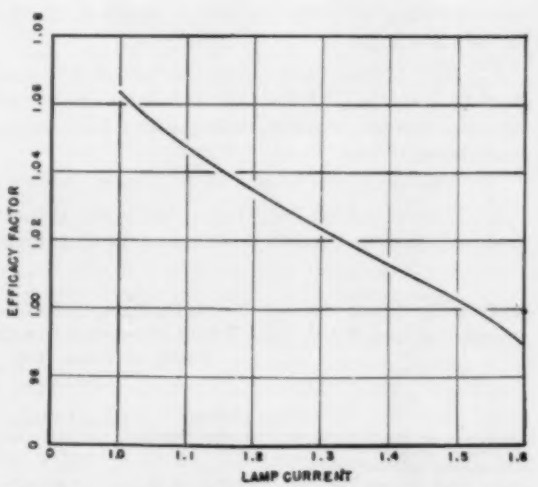

Figure 3. Variation in efficacy factor, K, with lamp current.

TABLE I—Series of Wattage and Light Output Measurements on 96-Inch 1.5-Ampere Lamp Operating at Various Currents. (Readings were taken on a reference ballast then quickly switched to a commercial ballast. Input voltage to commercial ballasts was adjusted to give same lamp currents.)

Lamp Current (Amperes)	Ballast	Lamp Watts	Foot-candles	Ratio Watts	Ratio Foot-candles
1.0	Reference	155	52		
	Commercial "A"	147	49	94.8	94.2
1.2	Reference	181	58.5		
	Commercial "A"	165	53	91.2	90.7
1.3	Reference	191	61		
	Commercial "A"	180	57	94.2	93.5
	Commercial "B"	185	58.5	96.9	95.9
1.4	Reference	200	63		
	Commercial "B"	190	59.5	95	94.5
	Commercial "C"	183	57.5	91.5	91.3
1.5	Reference	210	66		
	Commercial "B"	192	59.5	91.4	90.2
	Commercial "C"	197	61.5	93.8	93.2
1.54A	Reference	213	66.5		
	Commercial "B"	194	60	91.2	90.3
	Commercial "C"	198.5	61.5	93.2	92.5
1.6A	Reference	218	67		
	Commercial "B"	199	60.5	91.3	90.7
	Commercial "C"	200	60.5	91.7	90.7

special open-type luminaire was installed 6½ feet above the floor and one 96-inch lamp was installed. The room containing the fixture had conditioned air at 77F. The luminaire orientation was arranged to have a baffling effect to limit the air circulation to a minimum. Footcandle readings were taken on the floor directly under the luminaire.

A group of single-lamp commercial ballasts were selected and connected to the lamp. Separate filament transformers supplied cathode voltages necessary for proper heating (3.6 v). This allowed direct readings of lamp current, voltage, and wattage during the tests.

A series of readings were then taken on the lamp currents ranging from 1.0 to 1.6 amperes, in the following manner:

(1) The transformer-linear reactor supply was used to furnish 1.0 ampere to the lamp. Readings of lamp current, wattage, voltage, and footcandles were taken.

(2) The lamp was immediately switched over to a commercial ballast supply and the input voltage was adjusted to furnish 1.0 ampere to the lamp. Readings of current, wattage, voltage, and footcandles were taken.

(3) Tests were repeated for 1.2, 1.3, 1.4, 1.5 and 1.6 amperes and results are listed in Table I.

By comparing the lamp wattage ratios and light output ratios at the different currents, it can be seen that they are substantially the same. Therefore, the wattage ratio of a ballast can be used to determine its light output. To compute the per cent light output of a particular ballast as compared to the output on a reference ballast circuit at rated conditions, an efficacy factor for the difference in luminous efficacy between the lamp operation at the two lamp currents should be applied, then the light output computed by applying the efficacy factor to the ratio of lamp wattages. This formula would then be:

$$\text{Light output} = \text{Rated Lumen Output} \times \text{Lamp Wattage} \times K/\text{Rated Wattage}$$

The utility of this formula is shown by the results below.

Light Output on Commercial Ballasts At Rated Input Voltages

Next, a group of one- and two-lamp ballasts were selected for the 96-inch 1.5-ampere lamp. These ballasts were connected to one- and two-lamp combinations in the same luminaire set-up. First, a reference ballast circuit was connected at rated conditions to each lamp and the light output on the one- and two-lamp operation measured. When this was completed, the group of commercial ballasts was connected and measurements of input wattage, current, voltage, lamp wattage, current, voltage, current crest factor and light output were taken at rated input voltage. The per cent light output on each ballast was determined by this test. In addition to actual light output, a computed per cent light output was calculated based on the formula:

$$\text{Per Cent Light Output} = \text{Lamp Wattage} \times K/\text{Rated Wattage}$$

Where K is the Efficacy Factor of the lamp at the measured lamp current.

K used in the formula was taken directly from

TABLE II—Comparison of Per Cent Light Output on Single-Lamp Ballasts with Output on Reference Ballast Adjusted to give Rated Light Output. Computed Per Cent Light Output Based on Formula; Actual Light Output Is Result of Tests. (One 96-Inch 1.5-Ampere Lamp.)

	Lamp Watts	Lamp Amperes	Lamp Volts	Footcandles	Per Cent Light Output Computed	Per Cent Light Output Actual
Reference Ballast	213	1.54	168	66.5	100	100
Commercial Ballast "A"	180	1.3	183	57	86.1	85.7
Commercial Ballast "B"	183	1.4	178	57.5	86.8	86.5
Commercial Ballast "C"	190	1.4	178	59.5	90.0	90.5
Commercial Ballast "D"	203	1.58	170	62.5	94.9	94.0

TABLE III—Comparison of Per Cent Light Output on Two-Lamp Ballast with Output on Reference Ballast Adjusted To Give Rated Light Output. (Two 96-Inch 1.5-Ampere Lamps.)

Ballast	Input Watts	Lamp #1 Volts	Lamp #1 Amps	Lamp #1 Watts	Lamp #2 Volts	Lamp #2 Amps	Lamp #2 Watts	Foot-candles	Current Crest Factor	Per Cent Light Output Computed	Per Cent Light Output Actual
Reference Ballast		167	1.54	214	165	1.54	213	132	1.435	100	100
Commercial Ballast "E"	443	178	1.28	186	177	1.28	186	118	1.66	89.1	89.3
Commercial Ballast "F"	445	178	1.26	184	177	1.26	184	118	1.65	88.9	89.3
Commercial Ballast "G"	431	182	1.16	181	182	1.16	181	117	1.615	87.7	88.6
Commercial Ballast "H"	482	170	1.45	204	168	1.45	207	128	1.49	96.8	97.2
Commercial Ballast "I"	465	176	1.40	195	172	1.41	193	120	1.68	91.7	91.0

the curve of Fig. 3. The results are listed in Tables II and III. A comparison of actual per cent light output and computed per cent light output on this table indicated the accuracy that can be expected from this method.

Uses of Technique

In order to utilize this technique, the following steps can be taken:

(1) Connect up the lamp and ballast as required in a controlled ambient environment at 77F.

(2) Connect an ammeter and wattmeter in the lamp circuit.

(3) Separately heated cathodes can be used, but if a separate filament transformer supply is not available, the lamp current and wattage can be read while disconnecting one of the cathode leads and taking the readings of wattage and current in the other lead. Three watts should be subtracted from the wattage value of each lamp because of the increase in lamp wattage when operated without coil heat.

(4) Turn the lamp or lamps on and stabilize them.

(5) Record the lamp wattage and current for each lamp.

(6) Enter the curve of Fig. 3 with lamp current and read K at that value.

(7) Knowing the rated lumens and wattage of the lamp, all factors in the formula:

$$\text{Lument output} = \frac{\text{Rated Lumens} \times \text{Lamp Wattage} \times \text{Efficacy Factor } K}{\text{Rated Wattage}}$$

are known.

Conclusion

The use of electrical parameters of current and wattage to determine the light output of a commercial ballast should enable many agencies to estimate accurately the lumen output they will get from a particular ballast. This can be done without use of expensive light measuring devices and reference ballasts.

It should also be noted that the furnishing of rated lamp current by a commercial ballast does not assure rated light output. The crest factor of the current wave form must be low enough to give rated wattage before rated lumen output is assured.

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DISCUSSION

J. T. LAUGHLIN:* This paper again brings to the fore the problem the industry faces when it must make percentage light output measurements on 1.5-ampere lamps. Bluntly stated, the problem is one of making the lamp assume the rated electrical characteristics of voltage, current and wattage attributed to it by lamp manufacturers. This used to be simple before the advent of 800-ma, 1-ampere, and 1.5-ampere lamps. Two conditions which must prevail to achieve a bona fide test on 1.5-ampere lamps are:

(1) Right Lamp—The lamp must have the amount of mercury and gas fill pressure necessary to inherently yield the rated electrical characteristics.

(2) Right Environment—The lamp environment must be of the proper temperature and degree of air movement.

The burden imposed by the first condition, the right lamp, is no worse for 1.5-ampere lamps than for 40-watt rapid-start lamps, for example. Obviously, and understandably, relatively few of a group of lamps of a given type will have electrical characteristics within the $\pm$ 2½ per cent range specified by ASA Standard C82.1 for a reference lamp. Reference lamps may be obtained on request from lamp manufacturers or culled from a carton of lamps obtained from the local electrical supply house.

The second condition, however, the right environment, has posed an increasing burden as lamp currents have gone from 425 ma to 800 ma to 1 ampere to 1.5 amperes. These increasingly heavier loaded lamps have become hypersensitive to temperatures above the standard 77°C. Temperatures higher than 77°C cause the lamp voltage and, consequently, the lamp wattage and light to drop precipitously.

There are ominous implications inherent in this phenomena. It should be obvious to all that for maximum efficiency at normally experienced indoor temperatures, 1.5-ampere lamps should not be subjected to temperatures which are in excess of room ambient. Another way of saying the same thing is, don't subject the lamp to its own accumulated heat; after all, there are approximately 170 watts converted to heat in an eight-foot, 1.5-ampere lamp. How-

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ever, this is not really new. Even 425-ma lamps can experience a 16 per cent decrease from rated wattage in a four-lamp, fully enclosed ceiling mounted luminaire.

Whereas lamp manufacturers and light users look upon a fluorescent lamp as a 20 per cent efficient light source, ballast and luminaire manufacturers see it as an 80 per cent efficient heat source.

I do not see that the procedure outlined in this paper obviates either the lamp or environment requirements. It is still necessary for both requirements to be met; having fulfilled these conditions, is it not just as reasonable to use the conventional ASA procedure?

Apart from the fact that the right lamp and the right environment are still needed and hard to come by, I have another more basic question. Has the author considered the effect of lamp current crest factor? I ask this because it has been my understanding that light output for a given lamp wattage decreases as lamp current crest factor increases.[1] Fig. 3 shows a decrease in lumens/watts as lamp wattage is held constant and lamp current crest factor increases.

A hypothetical example will help to determine whether the system outlined in this paper and the information presented by R. N. Thayer[1] are compatible. Assume 1.6-ampere lamp current (107 per cent of nominal rating) which, according to Fig. 3 of Mr. Heffernan's paper, has an efficacy factor of 0.99. Further assume that the lamp current crest factor is such that the lamp delivers rated wattage. The formula presented in this paper would indicate a light output of 99 per cent. However, this same 107 per cent of nominal lamp current with a 1.68 lamp current crest factor would allow a lamp to deliver only 96.5 per cent light with rated lamp wattage according to Fig. 3 of Mr. Thayer's paper. There is a dilemma to be resolved. If lamp current crest factor must be plowed into the formula, the use of the proposed percentage light measurement technique would begin to become cumbersome as compared to the conventional ASA procedure.

It would be significant to know more about the single-lamp commercial ballasts used to obtain data for efficacy factors (Fig. 3). I question the procedure of varying ballast primary voltage to obtain lamp currents from 1.0 through 1.6 amperes. In so doing, the ballast open circuit voltage varies accordingly and affects lamp current crest factor. Therefore, there is really one dependent variable (efficacy factor) and two independent variables (lamp current and lamp current crest factor) in Fig. 3.

I suggest that users can best insure their investment in 1.5-ampere lamp ballasting equipment by specifying quality ballasts. Any reputable ballast manufacturer is more than willing to present reliable test data on his product. There is lots of room for discrimination, even among the most reputable ballast manufacturers.

1. Thayer, Richard N.: "Ballast Requirements for Fluorescent Lamps, "*Transactions of The Electrochemical Society*, Vol. 83, page 113 (1943).

A. E. Feinberg: Mr. Heffernan's development of an efficacy factor K is another method for stating the fact that light output and efficiency are affected by both the crest factor and the rms value of the lamp current. It has been known for quite some time that the lumen output of a lamp and the relative lumens per watt vary in accordance with the ratio of peak to rms current or, in other words, the crest factor. For example, 100 per cent lumens and lumens per watt would be obtained at rated wattage at a crest factor of 1.5; at 1.7 crest factor the percentage would drop to 96 per cent; at 1.85 crest factor the percentage would drop to 93 per cent.

Further experience has indicated that these ratios are not entirely consistent, but vary with the particular waveshape of the lamp current and the sharpness of the peak current. Consequently, it has been found that some waveshapes with poor crest factors have given relatively good light output.

It is quite possible that the efficacy factor shown in this paper may compensate for these differences, and has provided an additional tool to determine the approximate light output of a ballast, noting the wattage and the lamp current. The efficacy factor has been developed based upon the utilization of a reference ballast and a fairly sinusoidal lamp current waveshape. In Table I, there is closer correlation between commercial ballasts A and B and B and C than there is between the reference ballasts and the commercial ballasts. The percentage variation between the reference and the commercial ballasts appears to increase as the lamp current increases. We know that a commerical ballast, when operated below rated line voltage, develops a more sinusoidal waveshape than it does at line voltage. Consequently, the crest factors of the commercial ballasts are poorer at rated voltage than at the lower voltages. It is quite possible that the variations noted in Table I are due to the fact that the efficacy factor does not entirely compensate for variations in crest factor. It would appear, however, that correlation is sufficiently good to enable an approximation of output of a ballast with the aid of the efficacy factor.

It does not appear, however, that the application of this efficacy factor is going to enable commercial users to evaluate a ballast without the use of a standard for comparison. The reason for this is that the problem of stabilizing the lamp has not been eliminated. A lamp, when ignited, starts out with a relatively high wattage and low lamp current. As it warms up, the wattage drops and the lamp current usually increases. With lamps that are as difficult to stabilize as the 1.5-ampere lamps, the point of stabilization becomes quite critical. It is necessary to check lamp wattage, lamp voltage and lamp current in the process of determining whether stabilization has been achieved. Lamps themselves, which are used as reference lamps, may have variations in their characteristics of $\pm 2\frac{1}{2}$ per cent. In determining light output the normal procedure is to operate the lamp on a reference ballast to first determine whether or not the lamp itself is operating within reference lamp limit readings. A variation of five per cent is possible in accordance with the above tolerance limits. With this same reference ballast, variations in room temperature, drafts, etc., may quite readily cause considerable variation in the actual lamp wattage that is measured.

As I understand this paper, it is the author's intent to eliminate the use of a reference ballast, and to utilize the lamp and ballast being tested in such a manner as to determine the relative light output of the combination without the use of a reference ballast. There is no means available for the operator to determine, under these conditions, whether or not the lamps are stabilized. There also is no means available for the operator to determine whether or not the lamps in question fall within the limits of reference lamps. If the room happens to have a slight draft or a slightly low temperature, the light output readings obtained with this system will be considerably above those obtained with a normal measuring procedure. If the room temperature is slightly high, readings may be several watts below

*Advance Transformer Co., Chicago, Ill.

those which would be obtained under the correct operating conditions.

When tests are made in conjunction with a reference ballast, it is found that these variations, due to ambient temperature, etc., balance themselves out to a great degree, inasmuch as the same variations as influence the readings on the commercial ballasts influence those on the reference ballasts. The possible variation of watts actually measured by the reference ballast may very well be in the neighborhood of five per cent or better, due to the variations mentioned above. Again we have found that, utilizing room stabilization conditions, it is not possible to switch directly from a reference ballast to a commercial ballast and take an immediate reading. Since the commercial ballast may carry a different current than the reference ballast, it has been found desirable to allow an additional 15 to 20 minutes of stabilization time when switching from one ballast to another. The differences due to this time allowance, however, may be on the order of one per cent.

An additional factor is involved in the measurement of lamp wattage. The actual measurement of lamp wattage with rapid-start lamps has been and still is a difficult problem, which has led to the light output comparison system. Attempts to measure lamp wattage, as indicated here, could lead to considerable confusion. Wattage readings will vary depending upon which of the two cathode leads is disconnected. Normally, light meters are used to determine whether the disconnection of a cathode lead has made any change. They will also vary in accordance with which of the two cathode leads on the other end of the lamp is used for measurement purposes.

Too many possibilities of error appear present to warrant justification of this system.

DANIEL LOVINGER:* The author refers to the close relationship of the light output curve and the wattage curve for a given lamp. What little data we have taken would indicate that the light output curve would more nearly resemble lamp current, which is somewhat different from the lamp wattage curve. However, on a relative basis, I am sure the difference is slight enough to allow for the successful utilization of this type of formula.

The author's plan to improve the efficiency of lamp ballast testing is obviously a good one. The major problem would be that of knowing when the lamp is "stabilized." In addition, I am sure the author would have to assume that the lamps used were carefully selected "reference lamps." We have used the author's formula on several of our ballasts and have found that the formula worked successfully within an error of one to three per cent. This error, of course, may be due to the variation in our reference lamp. Another possible explanation could be the fact that the efficacy factor curve (Fig. 3) was apparently developed using a sinusoidal power supply. Certainly this can be true of a reference ballast lamp circuit, but commercial ballasts tend to have somewhat higher crest factor, and this may also induce error into the measurement system when comparing various manufacturers' ballasts.

I am sure the author has broken ground for a new way of making relative light output measurements on commercial ballasts that will, after some additional work, replace the rather elaborate and sometimes cumbersome method currently being used. I suggest that this paper be presented at the next ASA meeting and a program be set up to further develop this method of testing.

*General Electric Co., Danville, Ill.

M. E. ROBERTSON:* This method of determining relative light output offers a definite short cut for the laboratory which has only an occasional measurement to make. I feel, however, that it has two drawbacks.

First, the determination of the efficacy factor K is difficult, requiring the use of laboratory-type meters, standard reactors, and filament transformers. These lengthy tests must be performed for each lamp type. If the lamp manufacturers will furnish K factors for all of their lamps, this objection is overcome.

Secondly, the choice of efficacy factor K for a given comparison is dependent upon the measurement of rms current through the lamp from the test ballast. The author pointed out that ballast current waveform determines the lamp wattage. A ballast having a peaked wave, as compared to a ballast having a more nearly square wave, will have different values of rms current but could be delivering the same watts to the lamp. This could lead to a choice of the wrong efficacy factor K from the curve. The ballasts chosen by the author apparently had similar current waveforms but the commercial ballasts available may have widely different waveforms.

If the laboratory has the equipment to establish efficacy factors, then it must have both standard reactors and light meters. With this equipment, one need only take a footcandle reading with the standard reactor and with the ballast in question and express the latter as a percentage of the former.

The most important point to us is that the paper offers proof that it is not necessary to have the lamp under absolute standard conditions to check light output as long as lamp conditions are the same for both standard reactor and test ballast. This allows the use of present test methods and eliminates the need for a water bath or similar cooling media.

E. M. KOOKER:** Inasmuch as the only measurements required are electrical ones, which can be made with ordinary instruments, this new method of determining the light output ratio of a ballast does have the advantage of simplicity. It certainly merits further consideration by the industry, but its future usefulness, as compared to the more conventional methods involving measurement of lamp brightness, will depend primarily upon the degree of accuracy that can be attained.

In the introductory paragraphs, Mr. Heffernan points out that, in the case of heavily-loaded (1.5-ampere) lamps, one of the problems encountered in measuring light output ratio is the very long time often required for lamp stabilization. Since he specifically recommends this new method for use with the 1.5-ampere lamps, it seems to imply that the new method would avoid this long delay. Later in the paper, however, the fourth step in the suggested measurement technique is to "Turn on the lamp or lamps and stabilize them." I would like to ask whether this new method does, in fact, require that the lamps be brought to their final stabilized operating conditions, or whether it was the author's intention that the lamps be given only a short "warm up." In this connection I would also like to ask if the data in Tables II and III were taken with the lamps stabilized or unstabilized.

The author states that this new method is based on two fundamental relationships of certain lamp parameters. In support of the first of these, he offers the data shown

*Jefferson Electric Co., Bellwood, Ill.
**General Electric Co., Cleveland, Ohio.

graphically in Figs. 1, 2 and 3. These data are in excellent agreement with similar data which we have taken on other types and sizes of lamps, but we would like to point out that the measurements in both cases were on linear reactor circuits and do not necessarily apply to circuits having higher crest factors of lamp current.

Actually, from the standpoint of strict accuracy, the two fundamental relationships listed by the author should be supplemented by a third relationship showing that lamp efficiency, at constant current, varies with lamp current crest factor. According to data which we took several years ago, the change would be about 1½ per cent between crest factors of 1.5 and 1.85, which would cover the range usually encountered in commercial ballasts. This point is also borne out by the data which Mr. Heffernan himself has shown in Table I. In that table, it may be noted that the footcandle ratios are all one half to one per cent lower than the wattage ratios.

Another point requiring clarification is the term Rated Wattage, which appears in the formula. Is this the actual wattage of the lamp as measured on a reference ballast at line voltage, or is it merely a nominal value taken from a manufacturer's publication or an ASA standard? If it is only a nominal value, then we would expect the calculated light output ratios to be in error by the same per cent as the difference between the actual lamp watts and the published value. With normal variations in lamps this could, even for a 40-watt lamp, easily amount to two per cent or more.

A third consideration affecting the accuracy of the formula, at least for some of the highly-loaded lamps, is the question of lamp stabilization mentioned previously. If unstabilized lamps are used, the measurements of lamp watts would be too low by several per cent.

The author's data in Tables II and III indicate that the formula gives values within one per cent of those that would be determined by actual light output measurements. In view of the factors mentioned above, we find it hard to believe that this degree of reliability would always be attained. Even with the most precise methods so far developed, it is difficult to get much more than one half per cent accuracy unless more than a single measurement is taken. It would appear to us that the formula method would be useful only where an approximate answer will suffice.

One other item that might also be mentioned is Mr. Heffernan's suggestion that the term "lamp form factor" be substituted for "lamp power factor." We do agree that the term "power factor," as it is normally defined in engineering terminology, does not strictly apply to fluorescent lamps. We might also point out, however, that the term "form factor" has also been rigidly defined in engineering terminology, and it too does not fit the case of a fluorescent lamp. If a change is needed, perhaps the term "apparent power factor" might avoid stretching the proper meaning of the defined term.

J. C. HEFFERNAN:* Lamp stabilization is in itself a separate topic which should perhaps be the subject of a conference paper. Since it was not investigated for my paper I cannot at this time discuss it, except to point out that the stabilization problems mentioned by Messrs. Laughlin and Feinberg also appear in present-day methods of testing; these problems would not be the result of the adoption of the methods mentioned in the paper. As one who has sat in on many ASA meetings over the past two years when this was discussed, I realize the many areas of disagreement that exist today among the ballast and lamp manufacturers over the best method of measuring per cent light output.

I did not attempt to apply current crest factor into any formula because I feel that its effect can be clearly seen from an examination of Table I. For example, commercial ballast A, operating at 1.2 amperes, furnishes only 165 watts to the reference lamp while the reference ballast at the same current is furnishing 181 watts. Therefore, commercial ballast A (crest factor 1.72) furnishes 91.2 per cent of the power to the lamp that the reference ballast furnishes (crest factor 1.41). Light output on the commercial ballast A is 90.7 per cent of the output on the reference ballast. In other words, though you have a wide variation in lamp current crest factor, the effect of this variation is clearly indicated by the drop in lamp wattage when the poorer waveshape source is used. I might also indicate the magnitude of changes in crest factor on most of the commercial ballasts during these tests; from 1.5 at 70 per cent input voltage to 1.7 at 115 per cent input voltage.

Mr. Laughlin feels that Mr. Thayer's 1943 paper is not compatible with my paper. I find the opposite to be true. While Mr. Thayer indicates the decrease in lumens per watt as wattage is held constant and lamp current crest factor and rms current are increased, my paper quite clearly shows the decrease in light output to be expected when a ballast of poorer waveshape is operated at the same rms current as a reference ballast. In my paper the decrease in light output is tied directly to the difference in lamp wattage on the two ballasts, which is again an indication of the effect of the current crest factor on lamp performance.

While some concern appears to be indicated by Messrs. Feinberg and Laughlin about the possibility of a ballast design incorporating a very high crest factor, which would not produce the light output indicated by the paper, it should be remembered that the present ASA specifications on limiting lamp current crest factor to 1.7 maximum would certainly prevent any substantial deviation from present-day ballast construction.

As for Mr. Lovinger's suggestion that the paper be presented at the next ASA meeting and a program be set up to further develop this test method, I would be most willing, as a representative of a lamp manufacturer, to aid in these tests. However, I feel that nothing should be done along this line that would in any way further delay the time when the 95 per cent minimum light output ballast for the extra-high-output lamp becomes the accepted standard for the industry.

With regard to Mr. Robertson's question concerning the availability of efficacy curves from lamp manufacturers, I believe that this matter could be taken care of without any difficulty.

In answer to Mr. Kooker's question on lamp stabilization, all data reported in this paper were taken with lamps in their final stabilized operating condition. This is a necessity for proper use of this method.

With regard to lamp wattages, the rated watts mentioned are the actual measured values, using separately heated cathodes.

In order to eliminate variations in lamp wattage, it is suggested that reference lamps could be used in this type of testing with the data on actual lamp wattage supplied by the manufacturer.

*Author.

Lamp Performance Related to

Reference and Commercial Ballasts

This paper presents additional data on the use of mixed fill gases in fluorescent lamps with emphasis on how initial lamp performance is affected on reactor type reference ballasts and commercial ballasts. The majority of data concerns the addition of neon to argon in the 40-watt T12 lamp.

By J. F. GILMORE
R. E. HANSON

FLUORESCENT LAMPS contain, in addition to mercury vapor, a few millimeters' pressure of a rare gas, such as argon, in order to facilitate starting, protect the cathode from ion bombardment and provide required electrical characteristics. The use of a mixture of two or more rare gases has been shown to offer certain advantages which have made possible new or improved lamp types.[1, 2, 3] For example, the 25-watt T12 preheat lamp at its introduction used a 25 per cent neon, 75 per cent krypton mixture, later replaced by a 50 argon, 50 per cent krypton mixture which gave essentially the same operating characteristics. Although the 100-watt T17 argon-filled lamp still has some limited applications, it has been almost completely superseded by the 90-watt T17 lamp, filled with 50 per cent argon, 50 per cent krypton.

Fill gas mixtures continue to be of interest to the fluorescent lamp design engineer. Certain mixtures offer the possibility of increasing lumen output in a lamp of fixed geometry by developing higher wattage with high efficiency.[4] By use of mixed fill gases it may be possible to design lamps for optimum performance for specific ambient conditions and to provide lamp electrical characteristics more favorable to economic aspects of ballast design. In the use of mixed fill gases, the effect on lumen maintenance, lamp life, starting requirements and performance on various ballast circuits must be determined.

Effect of Fill Gas Mixtures on Lamp Starting

Lamp starting for this paper was considered satisfactory when 98 per cent of the lamps started at the minimum open-circuit voltage prescribed for the circuit in relation to 50F minimum ambient temperature and with starting aids as required. Starting requirements have been established by the industry for the 40-watt rapid-start lamps, as shown in American Standard C78.700-1958. The following conclusions have been reached as a result of many starting tests, using commercial ballasts representative of those now available.

Starting of 40-watt rapid-start lamps on series lead ballasts is satisfactory for argon-neon gas mixtures with neon content up to 50 per cent, at fill pressures 3.0 mm maximum. Neon content can be increased as fill pressure is reduced. For example, at 2.0 mm the neon content may be increased to 60 per cent.

The practical content of neon in argon-neon mixtures in 40-watt lamps on preheat lead-lag ballasts is limited by an objectionable flicker on a high reactance lead circuit. This occurs at neon content above 40 per cent with which neon content starting is still satisfactory.

Krypton additions to argon have a deleterious effect on lamp starting, especially in rapid-start types. Practically, krypton additions sufficient to significantly change argon-lamp electrical charac-

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teristics will be found to be excessive for satisfactory lamp starting. For this reason, mixtures containing krypton are not reported in subsequent data.

As a broad conclusion, it may be stated that within a practical fill pressure range, the use of neon in argon-neon mixtures does not affect lamp starting sufficiently to preclude its use in fluorescent lamps to improve other lamp characteristics.

Lamp Operation on Reference Ballasts and Commercial Ballasts

Test Procedure

Data were obtained on groups of 40-watt T12 rapid-start lamps of identical construction but having different compositions of argon-neon fill gas at different pressures. Extra anode area was provided to reduce end blackening anticipated in high-neon, low-pressure lamps. Lamps were burned to 100 hours and were stabilized before each reading in an ambient of 77F ± 1F.

The reference ballast conformed to specifications outlined in American Standard C82.3-1957, "American Standard Specification for Fluorescent Lamp Reference Ballasts." Lamp ratings are established on the basis of reference ballast operation. In these tests, the reference ballast was a reactor set to 439 ohms impedance, power factor of 7.5 per cent, for lamp operation from a supply voltage of 236 volts, without cathode heat. The reactor was operated for at least one hour before readings were taken.

If the use of argon-neon fill gas mixtures were to make possible a new or greatly improved fluorescent lamp, it would be highly desirable that the new or improved lamp would not only operate satisfactorily on ballasts in existing installations but also would show improved performance on installed ballasts. Accordingly, the tests were made on an available commercial ballast rather than on a newly designed ballast. The ballast used was specifically selected as being of good quality and representative of the majority of 40-watt series lead ballasts on the market. By "good quality" we mean that the specific ballast conformed to the specifications in American Standard C82.1-1960, "American Standard Specification for Fluorescent Lamp Ballasts." To obtain uniformity of readings, it was necessary to operate the ballast at rated voltage for a minimum of two hours before taking lamp data. One of the two lamps starting and operating on the series lead ballast was shunted by a capacitor to facilitate lamp starting. Data were taken on the non-shunted lamp, with the other lamp from the same test group. Supply voltage was 118 volts in all tests.

In reading lamp current, voltage and watts, the procedures conformed to the principles outlined in the "I.E.S. Guide for Electrical Measurement of Fluorescent Lamps—1954."

For convenience, most of the light-output data were taken by measuring the brightness of approximately one foot of lamp length at the center of the bare lamp. The usual safeguards were taken

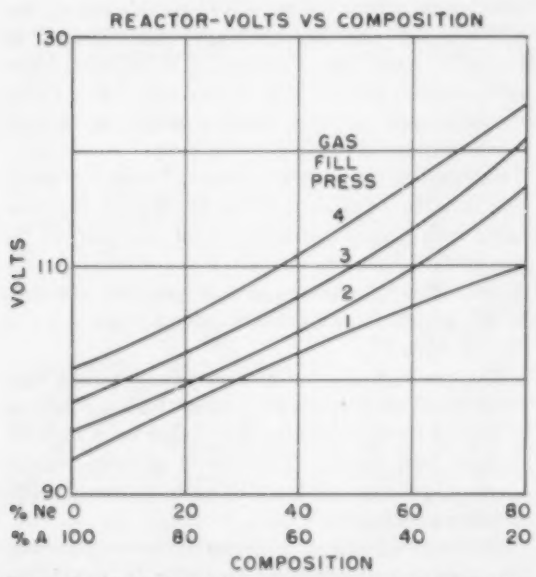

Figure 1. Voltage of 40-watt fluorescent lamp operating on reactor circuit as fill gas composition and pressure are varied.

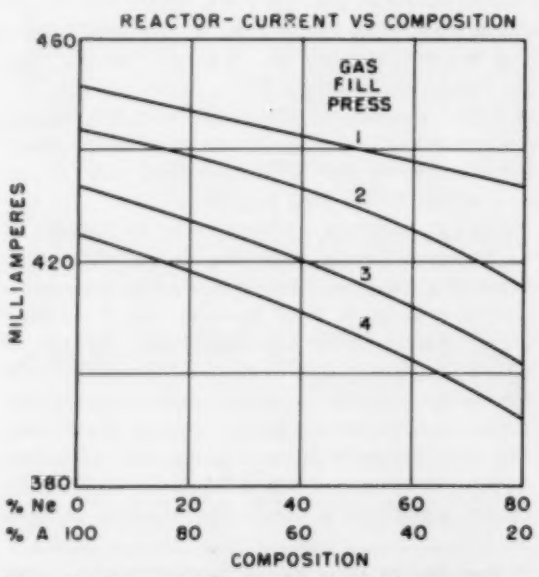

Figure 2. Current of 40-watt fluorescent lamp operating on reactor circuit as fill gas composition and pressure are varied.

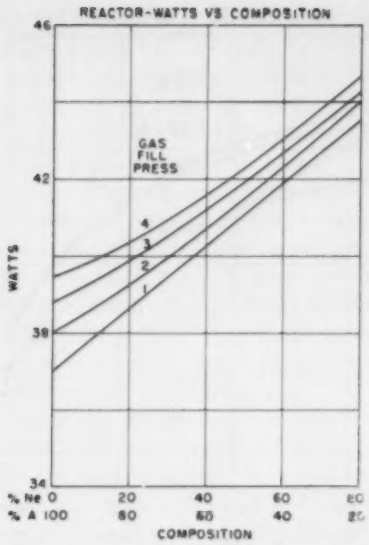

Figure 3. Wattage of a 40-watt fluorescent lamp operating on reactor circuit as fill gas composition and pressure are varied.

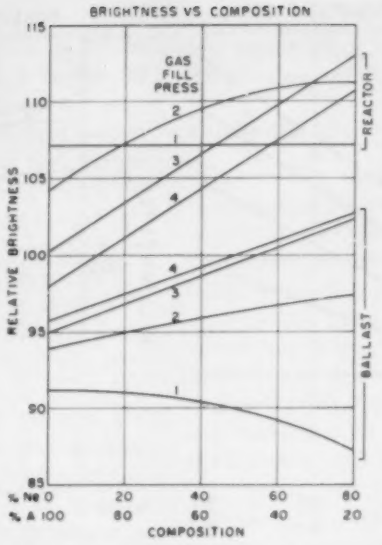

Figure 4. Output of 40-watt fluorescent lamp operating on reactor and series ballast circuits as fill gas composition and pressure are varied.

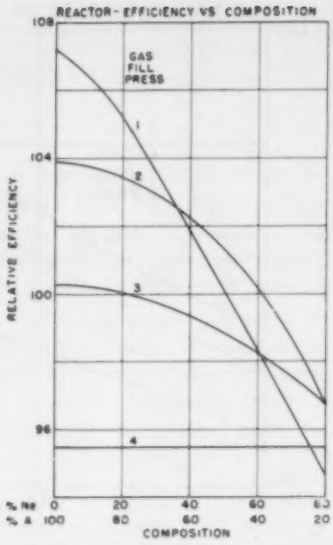

Figure 5. Efficiency of 40-watt fluorescent lamp operating on reactor circuit as fill gas composition and pressure are varied.

in regard to the measuring equipment and reproducibility of readings. Cross-checks between the brightness readings and light-output readings under standard photometry conditions were made with each gas mixture.

Lamp Performance on Reactor

As shown in Figs. 1, 2 and 3, as gas fill pressure and neon concentration are increased, the lamp voltage rises with consequent reduction in current and increase in lamp watts. In Fig. 4, the curves identified as "Reactor" show that with 100 per cent argon, light output increases as pressure is reduced. The pattern changes, however, as the neon concentration increases. The fill gas pressure for highest light output shifts progressively toward higher pressures with higher neon content. This effect relates to the efficiency of phosphor excitation, as shown in Fig. 5. The reduction of effiicency with low pressures of high neon content fill gas is due to higher elastic losses in the discharge and a shift in radiation characteristics toward non-exciting wave lengths.

With the data in Figs. 1 to 5, the lamp designer has the opportunity to assess the possibilities of argon-neon fill gas mixtures in the 40-watt lamp. As a base line, the standard argon lamp may be considered to be at 3.0-mm pressure, having operating characterisetics of 98 volts, 433 milliamperes, 38.8 watts, 100.5 relative brightness and 100.3 relative efficiency. (As noted previously, these test lamps had additional anode area which explains the slight differences from the characteristics of regular production lamps.) Using Figs. 1 to 5, we can determine the characteristics of a hypothetical 40-watt lamp having 2.0-mm fill gas pressure of a 60 per cent argon, 40 per cent neon mixture. The voltage will be 104 volts; current, 433 milliamperes; watts, 40.7; relative brightness, 109; and relative efficiency, 102.3. Thus, the hypothetical lamp will have, according to the reactor data, operating characteristics permitting operation on commercial 40-watt ballasts of preheat or rapid-start design, and will offer about 8 per cent more output at slightly higher effiicency than does the standard argon lamp. No starting difficulties would be anticipated, according to the prior discussion.

The hypothetical lamp has characteristics on the reactor that are attractive. Tests on such lamps showed that the same improvement relative to the argon lamp was obtained on good quality preheat ballasts. In the case of rapid-start ballasts, the pattern was different, as discussed below.

Lamp Performance on Series Lead Ballast

Figs. 6, 7 and 8 show the relationship between voltage, current and watts on the series lead ballast as fill gas pressure and composition are varied. Voltage and wattage increase with pressure and neon content. Except for the case of 1.0-mm pressure, the current shows the expected decrease with increase in lamp voltage. We are unable to explain the curve of 1.0-mm pressure in Fig. 7.

In Fig. 4, the curves identified as "Ballast"

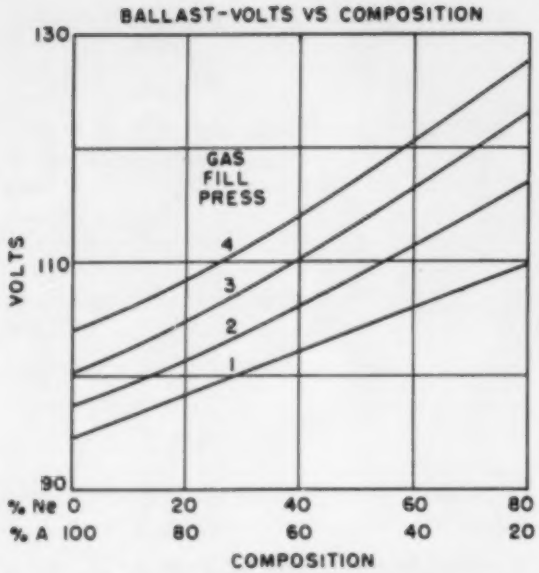

Figure 6. Voltage of 40-watt fluorescent lamp operating on series ballast as fill gas composition and pressure are varied.

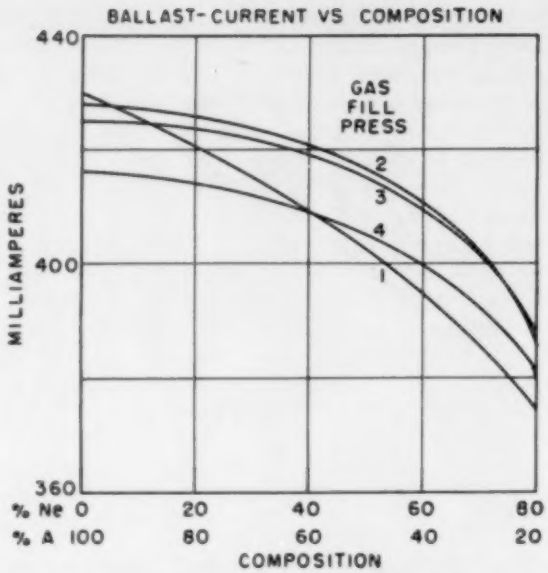

Figure 7. Current of 40-watt fluorescent lamp operating on series ballast as fill gas composition and pressure are varied.

show that with 100 per cent argon, light output decreases as pressure is reduced. Note again that the opposite is true on the reactor. Fig. 9 shows that efficiency is reduced at lower pressures of high neon content, as was the case on the reactor and for the same reasons.

The standard 3.0-mm argon lamp on the ballast operated at 101 volts, 426 milliamperes, 35.7 watts, 95 relative brightness and 101.8 relative effiicency. The relative brightness on the ballast is 94 per cent of that on the reactor, whereas the wattage on the ballast is 92 per cent of that on the reactor. Brightness does not decrease in direct proportion to wattage principally because cathode heat was supplied on the ballast and was not supplied on the reactor. These relations between reactor and ballast operation of the standard argon lamp conform to what is expected of good ballast design.

We find, however, that the hypothetical lamp with 2.0 mm of 60 per cent argon, 40 per cent neon

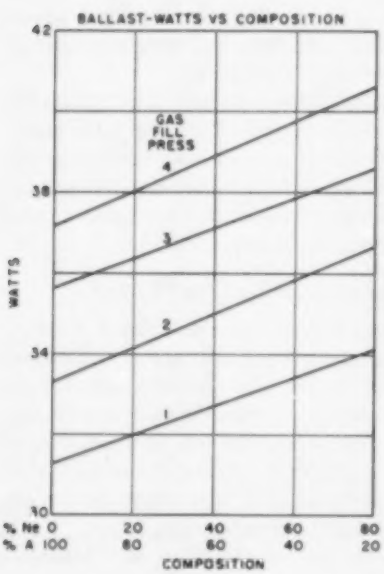

Figure 8 (left). Wattage of 40-watt fluorescent lamp operating on series ballast as fill gas composition and pressure are varied.

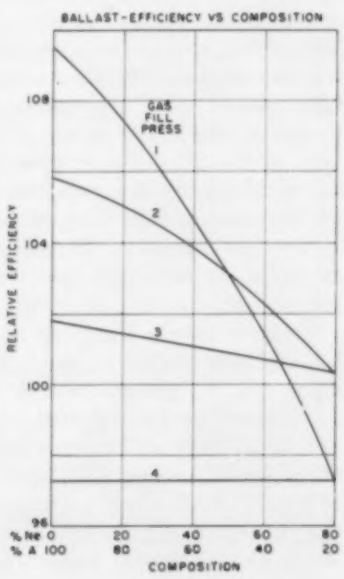

Figure 9. Efficiency of 40-watt fluorescent lamp operating on series ballast as fill gas composition and pressure are varied.

fill gas does not give the increased lumen output which would be expected. In Fig. 4, it is shown that the relative brightness is 97, which is only 89 per cent of the value obtained on the reactor. Compared to the standard argon lamp, the light output of the hypothetical lamp is only 2 per cent higher on the ballast although it was 8 per cent higher on the reactor. From Fig. 8 it is learned that the hypothetical lamp develops 35 watts on the ballast, or 86 per cent of the 40.7 watts developed on the reactor. This tendency of the ballast to develop a progressively lower percentage of the reactor wattage is more pronounced as neon content increases and pressure is reduced.

It is not technically difficult (but perhaps not economically desirable) to design a preheat ballast which will operate an argon-neon lamp at the same electrical values as are obtained on the reactor. This seems to be more difficult with the series lead ballast. One source of difficulty arises from the fact that with two lamps in series, the lamps reignite in sequence at each half cycle, thus introducing a time delay which results in increasing the current wave crest factor. With a given rms current, a higher current wave crest factor results in lower lamp wattage. With higher neon content, it has been observed that the reignition delay is more pronounced. It has been observed also that lower pressure has an adverse effect on current wave in the latter half of the cycle. From these and other observations it was concluded that in order to narrow the margin between the standard reactor and the commercial ballast, the current wave shape should be improved to approximate a sinusoidal wave.

One approach to improving the wave shape was to simulate the commercial series lead ballast using inductive and capacitive components that could be tested in several combinations. It was found possible to approximate the same relationship between standard argon and argon-neon mixture lamps as was obtained on the reactor. Under these conditions, the secondary flux density was about half of that believed to exist in the commercial ballast.

A second approach was to modify a commercial ballast to permit testing several combinations of primary winding, secondary winding, and core material, keeping the same design of magnetic circuit. The ballast size would not be affected appreciably by these changes. Over the range of primary and secondary flux tested, there was no significant improvement in the operation of argon-neon mixture lamps relative to argon lamps.

From our tests we have concluded that the commercial series lead ballast would have to be redesigned to a much greater size (and cost) to obtain with argon-neon mixture lamps the same relative performance between ballast and reactor as is obtained on argon lamps.

Conclusion

It has been shown that mixed fill gases can be used in fluorescent lamps to obtain higher lumen output and efficiency as ordinarily measured on reference ballasts. However, the operating characteristics of existing commercial ballasts in combination with lamp characteristics may result in poorer initial lamp performance than would be expected from reactor mersurements. Lamp design engineers, therefore, must carefully consider ballast characteristics in altering or creating lamp designs and predicting lamp performance.

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DISCUSSION

A. E. FEINBERG:* The authors have indicated a very realistic approach to the problem of lamps, ballasts and lighting. Far too often in the past, lamps have been designed independently of the ballast. In many cases, lamp modifications were made and the ballast designer was expected to undertake the application of an existing ballast to a slightly modified lamp wherein the differences, as related to the ballast, were not too readily apparent. Consequently, they are not evident until field problems appear or the lamp fails to live up to the designer's expectations.

The one point that has not been stressed in this paper is the fact that the lamp is intended to develop 40.7 watts as compared to the 38.8 watts of the standard lamp. If this lamp had operated successfully on a commercial ballast, it would have required a draw on a commercial ballast of approximately four watts more than what the ballast had been designed for. This increase of five per cent in output would have meant an increase in primary current requirements of the ballast and could have meant a ten per cent increase in ballast temperature. The significance of such an increase has apparently been overlooked by the authors. It is important from both the standpoint of the ballast manufacturer and the fixture manufacturer that such temperature changes due to lamp changes not be overlooked.

D. LOVINGER:** As a ballast designer, I agree that such things as fill pressure, gas mixture, and cathode construction are all critical factors which must be considered when providing proper lamp operation on commercial ballasts. At the same time, however, in the last several years ballast

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**Ballast Department, General Electric Co., Danville, Ill.

technology has progressed to the point where today's ballast designer can provide performance on commercial ballasts to nearly equal that of reference ballasts. To do this, however, he must be aware of the kinds of changes that have been made in lamps.

It would appear that in the last several years, significant improvement in lumen output and efficiencies have been brought about by variations in the same lamp construction features noted in the paper. These same newer lamps appear to have almost the same electrical characteristics as the so-called "standard lamp." Therefore, it is important that some consideration be given by the lamp manufacturers towards supplementing the ASA electrical characteristics with those pertinent design characteristics that will affect the performance of these newer lamps on the various commercial ballasts. Only in this way can the light user be assured the benefits of the new and ever increasing lamp technologies.

D. D. HINMAN:* It is gratifying that the data presented by the authors confirm, so well, similar data of our own. In most instances the small differences are consistent with the expected precision of such data.

One outstanding exception occurs in the relative lamp brightness on commercial ballasts. The conclusions in this paper imply that most of the gain obtained on a reference ballast with neon-containing lamps will be lost on a commercial ballast, and that it is not feasible to design a ballast which will avoid this loss. I do not agree with these conclusions.

Some of the 40-watt series rapid-start ballasts in existing installations will produce the higher lumens and lumens per watt that are indicated by reference ballast measurements on neon-argon mixed-gas lamps. The data from two such ballasts have already been reported.[1] There is, then, no insurmountable ballast design problem involved here.

In addition, the authors compare the mixed-gas lamps only with non-standard argon lamps made with large anodes. If a comparison were made with standard, commercially available, argon lamps, many of which have a filling pressure less than 3 mm, then the lamps containing neon and large anodes would show a greater advantage than indicated in the paper, especially on the commercial ballast.

1. Hinman, D. D. and Fox, R. S.: "40-Watt Fluorescent Lamp with Higher Light Output," Fig. 7, ILLUMINATING ENGINEERING, Vol. LVI, No. 3—Section II, p. 222 (March, 1961).

W. P. LOWELL, JR.:** Work in our laboratory confirms the principal finding of the authors—*i.e.*, that neon-argon mixed gas 40-watt lamps do not perform as well on commercial ballasts as is indicated by operation on reference reactors. Our data may differ in degree, but that is probably due to difference in the ballasts tested.

*General Electric Co., Cleveland, Ohio.
**Sylvania Electric Products Inc., Salem, Mass.

In addition to finding that the initial lumen output of neon-argon 40-watt lamps on commercial ballasts was not as high as that predicted by operation on standard reactors, we found that the neon-argon 40-watt lamps had poorer lumen maintenance, greater discoloration and shorter life than did standard argon-filled 40-watt lamps.

One question for the authors: Can you predict any economical design of commercial ballast which might improve the operation of mixed gas lamps?

J. F. GILMORE AND R. E. HANSON:* It is pleasing to note that the findings reported by the discussers parallel our own results, with only minor differences. The primary difference is in the degree of deviation and it is surmised that this deviation is due to the variations of the commercial ballast used for comparison purposes.

Mr. Feinberg's reference to the temperature problem is very much appreciated. During the test work for obtaining data related to this paper, no temperature rise data were secured. We were aware, however, that the temperature would be affected because of the redistribution of the ballast currents. It was felt that the problem of temperature rise, although important, was an area requiring extensive testing and was not within the scope of this paper. The example Mr. Feinberg cited in his discussion points up the importance of the necessity for such test work when considering operation of a newly designed lamp from a present commercial ballast.

The problem of standardization of lamp and ballast data mentioned by Mr. Lovinger is ever present. We agree that pertinent data on all new developments should be standardized wherever possible.

Mr. Hinman's disagreement with our results may be accounted for by considering the difference in ballast operating temperature. It was found that the ballast temperature was an important factor. Our data indicated that a higher lumen ratio was secured with a cold ballast than with a ballast which had been temperature stabilized, as was done in our tests. The designs of several manufacturers were tested and we found no commercial ballast that gave the same lumen ratio for both argon and neon-argon lamps.

Mr. Hinman also commented on the relative performance of the argon lamps used and commercially available argon lamps when compared to the mixed gas design. He is correct in stating that a greater advantage would have been obtained with the commercially available argon lamp. However, the advantage is small—three per cent as compared to the two per cent reported.

Mr. Lowell asked if we could predict an economical design of commercial ballast which might improve the operation of mixed gas lamps. With our present knowledge of the ballast industry, we believe that a design which would improve the relative performance of the mixed gas lamp and argon lamp, to the required degree, would not be competitive with the system the industry is presently producing.

*Authors.

Photometry of Luminaires Using Highly-Loaded Fluorescent Lamps

By G. A. HORTON
R. R. FRENCH
JOHN B. ARENS

Huge photometric laboratories have usually been required for adequate testing of fluorescent luminaires. This paper describes the design and construction of a so-called "point source" photometer in which adequate test distances for eight-foot luminaires in normal burning position may be obtained within a nominal ceiling height of 12 feet. Coefficients of utilization calculated from these test results compared with actual measurements of the luminaires in an Interflectance Room check out its accuracy.

INTRODUCTION of extended light sources and, in particular, the extra-high-output (EHO) fluorescent lamps has placed greater burden upon photometric laboratory testing facilities. Theoretically, the results of photometric tests should not be expressed in candlepower unless the measurements are made at such a distance from the light source that it may be regarded as practically a point. When measurements are made at distances such that the inverse square law does not apply, the results should be stated in "apparent candlepower" at the particular distance employed and this distance should always be specifically stated. The "apparent candlepower" of an extended source measured at a specific distance is the candlepower of a point source of light which would produce the same illumination at that distance.

Several papers have been written[1,2] which show that for 99.5 per cent precision in candlepower measurement, a photometric test distance of five times the maximum dimension of a fluorescent lamp is satisfactory. Beyond the five times maximum dimension, the measurements fall within the realm of the law of diminishing returns.

The accuracy of coefficients of utilization for indoor luminaires as calculated by the IES Recommended Method,[3] which is based upon point sources, depends upon the accuracy of the determination of the lumens within the annular zones as calculated from the luminaire candlepower distribution data. This, in turn, depends upon the accuracy of the candlepower measurements which is theoretically dependent upon test distance.[12] However, it should be pointed out that indoor fluorescent luminaires are not always applied in typical installations at distances approaching five times their maximum dimensions.

In measuring candlepower or luminous intensity, it is usual to measure the illumination E, which is produced by a source, at a convenient distance and multiply this value by the distance in feet squared (D^2). If the measurements of illumination are made at several increasing distances it will be found that the illumination E will decrease rapidly as the distance D increases. However, the values of ED^2 are found to approach a constant as D increases and sooner or later the product ED^2 becomes essentially independent of D. This limiting value of ED^2 is a measure of the intensity of the source and is called luminous intensity or candlepower I and may be expressed as:

$$I = \lim_{D \to \infty} ED^2$$

Let us now consider a line source of light radiating according to the cosine law (see Fig. 1).

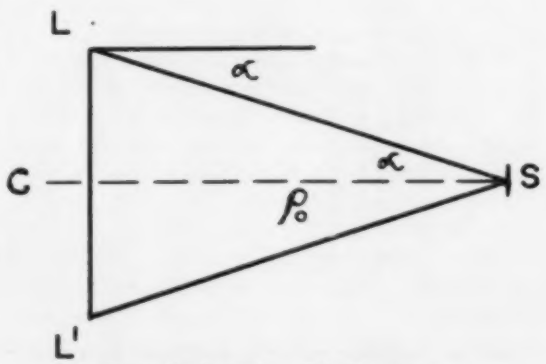

Figure 1. Long line of light source.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHORS: Westinghouse Electric Corp., Lighting Division, Cleveland, Ohio. Accepted by the Papers Committee as a Transaction of IES.

Let LL' = line source of light
B = luminance or brightness of source
A = area of source
I_o = luminous intensity perpendicular to source
$I_o = B \times A$
A = element of surface at L.

The luminous intensity of a surface element normal to the source is $\Delta I_o = B\Delta A$. However, in the direction of S, the luminous intensity due to a surface element at L is only $\Delta I_\alpha = \Delta I_o \cos\alpha = B\Delta A \cos\alpha$.

The illumination at S produced by ΔA is

$$E_s = \frac{\Delta I_\alpha \cos CSL}{(LS)^2} \quad \text{but } LS = \frac{\rho_o}{\cos\alpha}$$

$$= \frac{\Delta I_o \cos^2\alpha}{\frac{\rho_o^2}{\cos^2\alpha}}$$

$$= \frac{\Delta I_o \cos^4\alpha}{\rho_o^2}$$

That portion of the illumination at S contributed by a surface element at L is lesser by the factor $\cos^4\alpha$ than the value that would be included if the simple inverse square law was used.

Therefore, the illumination as calculated by the simple inverse square would be too large and must be corrected if it is to agree with the illumination as measured by a cosine corrected photometer located at S.

Yamanouti[4] has developed correction factors C for simple geometrical shapes radiating according to the cosine law, the corrections to be applied to the illumination at a point S as calculated by the simple inverse square (see Figs. 2 and 3). As may

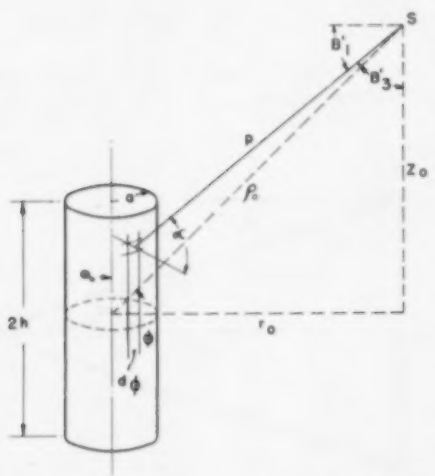

Figure 2. Uniformly radiating cylindrical light source with length $2h$ and radius a.

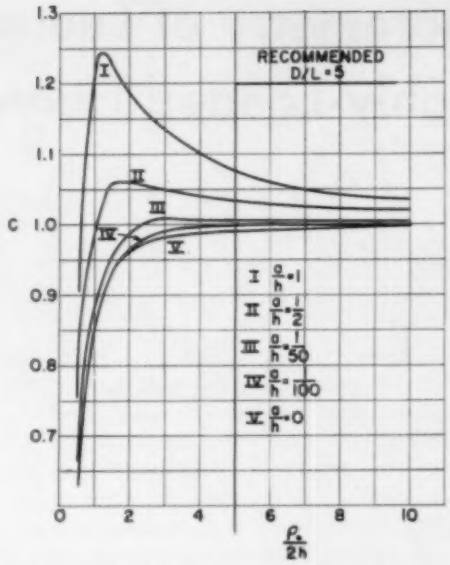

Figure 3. Corrections C to be applied to illumination at point S as calculated by simple inverse square.

be seen, correction curves have been plotted for circular cylindrical sources of different shapes and sizes for different ratios of a/h in the direction $z_o = 0$. The formula for the calculations is as follows:

$$C = \frac{\rho_o}{4ah \cdot \sin\theta_0}\left[a \tan^{-1}\frac{2h\sqrt{r_0^2 - a^2}}{r_0^2 + z_0^2 - a^2 - h^2}\right.$$

$$-\frac{z_0}{2}\left\{\frac{1+\mu_1 l}{\sqrt{\mu_1}}\cot^{-1}\sqrt{\frac{l}{\mu_1}} + \frac{1+\mu_2 l}{\sqrt{\mu_2}}\cot^{-1}\sqrt{\frac{l}{\mu_2}}\right\}$$

$$+\frac{h}{2}\left\{(\mu_1+1)\frac{1}{\sqrt{\mu_1}}\cot^{-1}\sqrt{\frac{l}{\mu_1}} + (\mu_2+1)\frac{1}{\sqrt{\mu_2}}\right.$$

$$\left.\left.\times\cot^{-1}\sqrt{\frac{l}{\mu_2}} - 4\cot^{-1}\sqrt{l}\right\}\right]$$

where $l = \dfrac{r_0+a}{r_0-a}$, $\quad \mu_1 = \dfrac{(z_0-h)^2+(r_0+a)^2}{(z_0-h)^2+(r_0-a)^2}$,

and $\quad \mu_2 = \dfrac{(z_0+h)^2+(r_0+a)^2}{(z_0+h)^2+(r_0-a)^2}$

If we may make the assumption that the diffusing cylinders are similar in light output distribution to a CIE general diffuse fluorescent luminaire, we can perhaps begin to see a reason why some photometric laboratories report a higher calculated efficiency for four-foot fluorescent luminaires than for eight-foot luminaires of the same cross section, when the candlepower distributions are measured

in each case at the recommended test distance of five times the maximum dimension of the luminaire ($D/L = 5$). It also begins to become apparent that the distance from the source at which the inverse square law begins to be applicable depends not only upon the size of the source and the precision required, but also upon the shape of the source.

At present, there seems to be available two distinct types of extra high output fluorescent lamps —those having circular cross sections[5] and those with non-circular cross sections.[6] However, both operate on the same physical principle that the most efficient operation of fluorescent lamps is obtained at a mercury vapor pressure of about 6 to 10 microns, which is the vapor pressure of mercury between 40° and 45°C. This mercury pressure is determined by the coldest spot on the bulb wall.

In the operation of conventional lower-loaded fluorescent lamps (HO) of circular cross section, the coldest spot of the lamp is usually the bulb wall at approximately the lamp center.

The extra high light output of the circular cross section type of EHO fluorescent lamp is obtained by the use of circular heat reflecting shields mounted between the filaments and lamp ends. The purpose of these shields is to prevent radiation from the heated filaments from striking the bulb near the bases, and to break up convection currents in the heated gas about the filaments so heat is not carried to the ends of the lamp. This effectively gives a cool chamber at each end of the lamp in which excess mercury may condense. Bulbs for these lamps are generally of the T-12 size.

The other type of extra-high-output fluorescent lamp currently available utilizes a T-17 grooved type bulb. For control of mercury vapor pressure, the improved version of this lamp[7] has one specially constructed groove on each side of the tube near the center of the lamp. By providing cooling pockets, these grooves regulate pressure, regardless of their orientation about the long axis of the lamp. However, best performance is said to be obtained with the grooves oriented sideways. It is important for cool areas to be present near the center of the lamp, where mercury prefers to collect for reasons other than temperature differences, as a result of electrophoresis effects.

Initially, in extra-high-output fluorescent lamps, the drops of mercury are distributed randomly throughout the lamp. For initial stabilization, the time required for the excess mercury to migrate to the coldest bulb wall spot may be 24 hours or more. However, providing the lamps are not disturbed in any manner, restabilization, the next time the lamps are started, may require as little as 30 minutes.

Obviously, the operating position for proper stabilization of extra-high-output lamps is horizontal, to enable the excess mercury to condense out in the designed positions. However, it should be pointed out that light output and electrical values may become constant, that is, the lamp may stabilize in other positions or orientations but the light output may not be the same as for the designed position. The term "conditioned" has been proposed for extra-high-output-lamps when stabilized in their normal end use position (horizontal). When extra-high-output lamps are used in completely enclosed luminaires, such as street lights, the end portion of the stabilizing period may occur in a few minutes and be accompanied by a sudden rise in light output and lamp voltage. In addition to orientation, these lamps are extremely sensitive to temperature changes, drafts and mechanical agitation. Also, lumen maintenance curves do not seem to show any indication of leveling off but rather a more or less steady drop during lamp life. It appears, therefore, that the usual recommended seasoning period of 200 hours[12] is sufficient for this type of lamp. EHO lamps operated in series from the same ballast do not always necessarily stabilize at the same time. The drops of excess mercury which condense out in these lamps show some tendency to adhere to the inside lamp coating.

In constructing a photometer, or more strictly speaking a goniometer, for the satisfactory handling of luminaires using extra-high-output lamps, the principal requirements appear to be as follows:

(1) The luminaire at all times must be maintained in its normal burning position (horizontal).

(2) If the conditions are such that the luminaire must be moved, instead of the photocell, to obtain the candlepower distributions, then mechanical motion must be sufficiently slow, smooth and free of sudden starts and stops that the excess mercury in the lamps will not be displaced once the lamps have stabilized.

(3) The temperature of the photometric laboratory should be maintained at 77°F ± 1°F and the environment should be as draft-free as possible. Normal indoor rates of air movement are one to three miles per hour. Minimum perceptible draft is approximately one mile per hour.

If one is permitted to start from the beginning and design a new laboratory, the solution of the above problems may be relatively simple. However, in the authors' case, it was desired to accomplish so-called point source photometry for luminaires up to and including eight feet in length, maintain the luminaire in normal operating position, yet make the installation in a twelve-foot ceiling height. This imposed unusually severe restrictions on the mechanical design of the goniometer. It is obviously impossible in this case to suspend an eight-

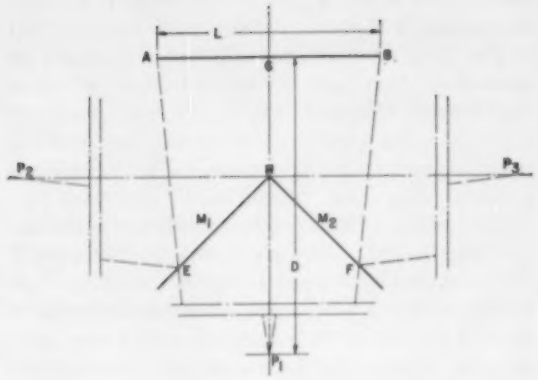

Figure 4. Optical ray trace for photometer.

foot luminaire from the ceiling and make candlepower distribution measurements all about it at a test distance of forty feet. Likewise, because of clearances involved, it is not possible to utilize a single mirror by methods already in existence.[8] However, since adequate horizontal space was available, it was possible to utilize two mirrors in such manner that the luminaire image is accurately split into two parts. This is best illustrated by the ray trace of Fig. 4. Referring to this illustration, consider the axis of a luminaire of length L to be represented by the line AB and the photocell to be located at P_1, a distance D of five times the luminaire length away. If two mirrors M_1 and M_2 are set at forty-five degrees to the photometer axis of rotation P_2 P_3 as shown, then clearly the ray trace becomes AEP_2, GHP_2, and BFP_3, GHP_3 instead of AP_1 — BP_1. Then, if the luminaire is freely pivoted about the axis AB and at the same time its position in space is maintained the same relative to the mirrors, if the whole assembly is rotated about the axis P_2 P_3, it is possible to make vertical candlepower distributions about the luminaire. Vertical distributions through different horizontal angles may be made by rotating the luminaire laterally about a vertical axis at G. The scheme of construction is also illustrated by Fig. 5, which shows the mirrors at nadir viewing the luminaire at zero degrees vertical angle, and Fig. 6, which shows the mirrors at zenith viewing the luminaire at 180 degrees vertical. The construction is further clarified by Fig. 7, which shows the rollers upon which the goniometer rotates. Fig. 8 is a view of the goniometer including one of the photocell screening boxes, the constant speed motor drive, control panels, etc.

The photocells at P_2 and P_3 are of the barrier-layer type and, ordinarily, due to the optical design of the goniometer, each cell views one half of the luminaire. However, in certain circumstances, particularly in the case of parallel-to-curb-mounted fluorescent street light, the illumination on the two cells may be unequal and there are times when one cell may not be illuminated at all. In all these cases it has been shown that when the cell outputs are connected in parallel the response of the cell array is essentially correct.[9]

If luminaires utilizing EHO lamps of circular cross section are to be photometered, the relative method of photometry may conveniently be employed. In this case, it is probably best to check the individual test lamps for their lumen/candlepower ratios because of the dark end zones, rather than trust the 9.25 ratio[10] commonly used for lower loaded fluorescent lamps. Fig. 9 shows the calibration rack in place on the goniometer where the luminaire would ordinarily be suspended. It is best to determine the position of the lamps about their own axes when installed in the luminaire and then transfer them to the calibration rack as carefully as possible without tilting or rotation about lamp axes in order not to disturb the distribution of mercury once the lamps have stabilized. Fig. 10

Figure 5 (left). View from one photocell position showing luminaire on goniometer with mirrors at nadir.

Figure 6 (right). View from one photocell position showing luminaire on goniometer with mirrors at zenith.

Figure 7. View showing goniometer mounted upon its drive rollers.

Figure 8. View of goniometer including one photocell screening box, constant speed motor drive, control panel, etc.

is another view of the calibration set-up showing the lamps being energized from the ballast in the luminaire to be photometered. One of the photocell screening boxes is seen in the background.

If luminaires utilizing lamps of non-circular cross section are to be photometered, the direct method of photometry may be employed conveniently, particularly if a photometric integrating sphere is available. The position of each test lamp in the luminaire about its own axis is noted, then each lamp is carefully transferred in this position to the integrating sphere and lumen-rated while operating from its own luminaire assigned ballast connections. The photometer is then calibrated in candlepower per division by using stable fluorescent lumen and/or candlepower standards of the same color as the test lamps, these lamps being mounted in the calibration rack.

An alternative procedure to the so-called point-source photometry described above for luminaires utilizing EHO lamps has been proposed to the IES Committee for Testing Procedures by one of its members.[11] This is as follows:

"(1) Mount the luminaire in its normal mounting position (as specified by the manufacturer). The room should be as black as possible with nearly zero internal reflections. The unit should have a clear space below of 12 x 12 x 12 feet for a

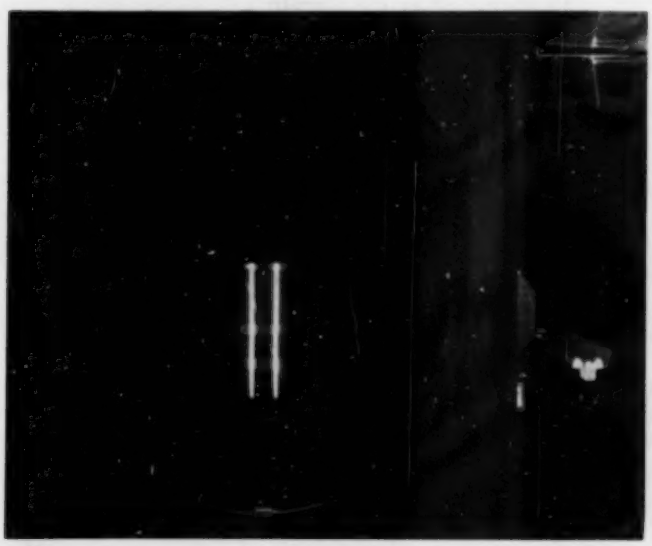

Figure 9. View of calibration rack in place on goniometer.

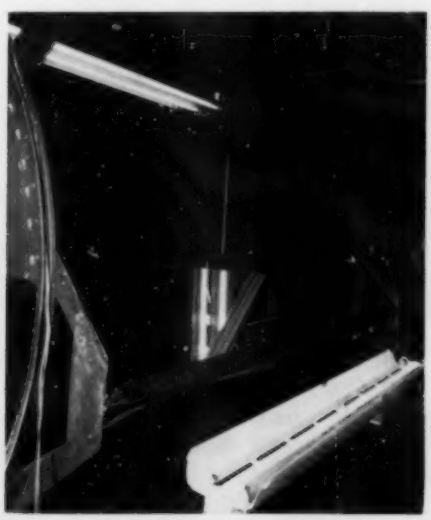

Figure 10. Calibration set-up showing lamps energized from test luminaire ballast.

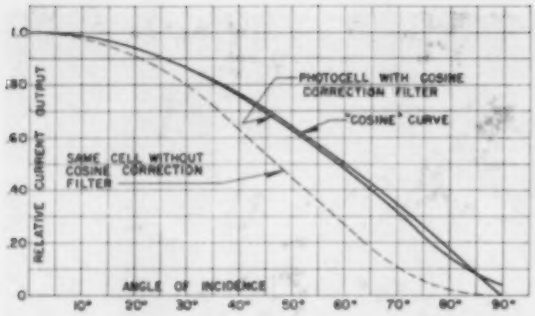

Figure 11. Curves illustrating degree of cosine correction of barrier layer photocell used in tests.

direct unit or 12 x 12 x 12 feet above for an indirect unit.

(2) Control the ambient air temperature to 25°C.

(3) Operate luminaire at rated voltage until the output is stable.

(4) Consider that the unit is at the center of a 10-foot radius sphere. Arrange a shielded cosine-corrected photocell to rotate in a vertical plane on a 10-foot radius through the center of the sphere. Thus "A" (perpendicular), "B" (parallel), and "C" (45 degrees) plane vertical traverses can be made on the surface of the sphere. Note: The unit is turned in its normal mounting position to the *A*, *B*, and *C* planes.

(5) Determine the average illumination (in lumens/ft.^{2}) on the surface of the sphere at 5, 15, 25, 35 - - - - 85 - - - 175 degrees. Compute the total flux in each zone. (flux = illumination × area of zone on sphere). Add up the total zonal flux = luminaire output.

(6) Repeat 1-5 for the bare lamps. This gives lamp input.

(7) Efficiency $= \dfrac{\text{luminaire output}}{\text{lamp input}}$

(8) Zonal flux is obtained from Step 5. Use this directly in K_u calculations.

(9) Zonal candlepower, *I* (average), if needed for distribution curves is obtained by standard formula:

Zonal flux (known) = $I_{ave.}$ × zonal constant (known)

The above procedure is entirely accurate within the limits of zonal averages for determining efficiency. It may (or may not) give slightly different values of $I_{ave.}$ than the standard procedure using a 40-foot test distance (for an 8-foot fixture). The latter is unimportant since the zonal flux values are more nearly those found in practice wherein a 10-foot distance is more representative than a 40-foot distance in interiors."

It was felt that a comparison of this method with the one used by the authors was in order. To this end, fluorescent luminaires were photometered at the recommended test distance of five times luminaire length[12] with a non-cosine corrected photocell and also at a distance of 1.25 times luminaire length ($D/L = 10/8$) with a cosine-corrected photocell as recommended above. The degree of cosine correction for the cell used is shown in Fig. 11. The results are shown in Table I. Examination of the data in Table I shows that candlepower values at nadir and zenith are lower when the luminaire is photometered at $D/L = 1.25$, but that the luminaire efficiency is approximately the same in both cases, which is as expected.[13, 1, 2]

Tables of Coefficients of Utilization were prepared for the luminaire photometered at both $D/L = 5$ and $D/L = 1.25$ with results as shown in Tables II and III, respectively. In general, the coefficients for the larger room ratios tend to be slightly higher for the luminaire photometered at $D/L = 1.25$. It was necessary to carry the coefficients out to three places to clearly see this trend.

Since an Interflectance Room of limited dimensions was available[14] the coefficients of utilization for four-foot fluorescent luminaires photometered at distances of five feet and 20 feet were checked out. The size of the room was 9 by 9 feet with ceiling adjustable from 9 to 11 feet above floor. Accordingly, data were taken for four luminaires in standard array suspension mounted at one-third the distance from the ceiling to the work plane.[15] Footcandle measurements were made using the cosine corrected photocell on a plane 30 inches above the floor.[15] The ceiling, walls and floor were coated with flat neutral paint of reflectances as tabulated in Table IV, all reflectances being measured with a type of reflectometer which has been described in the literature.[16] Measurements were

TABLE I.

Vertical Angles	$D/L = 5$ Average Candlepower	$D/L = 5$ Average Lumens	$D/L = 1.25$ Average Candlepower	$D/L = 1.25$ Average Lumens
0°	1552	....	1467	....
5	1526	145	1466	139
15	1529	434	1452	412
25	1422	658	1371	635
35	1147	720	1153	724
45	805	622	862	667
55	504	452	564	506
65	286	284	317	315
75	150	158	152	161
85	63	69	60	65
90	68	....	74	....
95	127	138	139	152
105	343	364	389	412
115	704	699	753	748
125	996	893	1036	929
135	1187	918	1206	933
145	1329	834	1294	813
155	1397	647	1333	617
165	1402	398	1327	377
175	1393	132	1309	124
180	1386	....	1312	....
Totals	.....	8565	....	8729
Luminaire	Efficiencies....	86.9%		88.5%

taken while the ambient temperature was 77°F ± 1°F. Results of a typical set of data are shown in Table IV. These results show that the trend is for the I room with 11-foot ceiling height(measured footcandles) to check more closely with the calculated footcandles from the luminaire photometric test at 20 feet, and for the H room with 9-foot ceiling height (measured footcandles) to check more closely with the calculated footcandles for the luminaire photometric test at 5 feet, which is to be expected.

Regardless of what test distance is used in photometry of fluorescent luminaires, the goniometer described in this paper will facilitate candlepower distribution measurements. From the test data presented, it appears that shorter photometric test distances utilizing cosine-corrected photocells may be satisfactory for interior installations where

TABLE II—Coefficients of Utilization Calculated from Photometric Results of Luminaire Tested at $D/L = 5$.

APPLICATION ENGINEERING DATA

Distribution	Floor Refl. %		10									30	
% Bare Lamp	Ceiling Refl. %		80			70			50			80	
	Wall Refl. %		50	30	10	50	30	10	50	30	10	50	30
	Room Ratio	Room Index	COEFFICIENTS OF UTILIZATION* (× .001)										
	0.6	J	244	188	157	232	184	166	214	174	144	246	192
C-I-E %	0.8	I	316	258	218	304	250	212	274	230	199	324	263
Luminaire	1.0	H	379	315	272	359	303	262	322	277	243	393	323
↑	1.25	G	441	375	331	417	360	317	368	323	288	462	387
↓	1.5	F	490	424	377	460	403	359	404	358	325	517	442
Maint. Factor	2.0	E	559	496	447	524	467	424	450	410	376	598	521
(× .01)	2.5	D	606	548	501	561	512	473	485	446	416	658	584
Good	3.0	C	638	587	542	594	554	510	508	461	445	703	632
Med.	4.0	B	682	639	599	631	595	562	540	511	487	761	705
Poor	5.0	A	713	676	639	658	629	599	559	536	515	808	763

*Calculated by approved IES Method.

TABLE III—Coefficients of Utilization Calculated from Photometric Results of Luminaire Tested at $D/L = 1.25$.

APPLICATION ENGINEERING DATA

Distribution	Floor Refl. %		10									30	
% Bare Lamp	Ceiling Refl. %		80			70			50			80	
	Wall Refl. %		50	30	10	50	30	10	50	30	10	50	30
	Room Ratio	Room Index	COEFFICIENTS OF UTILIZATION* (× .001)										
	0.6	J	244	188	154	233	183	150	214	172	143	245	191
C-I-E %	0.8	I	319	257	218	306	250	211	275	231	198	325	263
Luminaire	1.0	H	383	317	272	363	305	265	320	279	244	395	324
↑	1.25	G	447	379	332	422	363	319	373	325	289	465	390
↓	1.5	F	497	428	381	467	408	363	409	361	328	523	446
Maint. Factor	2.0	E	564	499	450	531	472	426	459	414	379	605	524
(× .01)	2.5	D	614	555	506	570	521	479	490	452	421	667	590
Good	3.0	C	649	597	550	604	559	519	517	482	453	711	640
Med.	4.0	B	694	650	607	644	607	572	549	520	495	777	715
Poor	5.0	A	725	701	648	671	640	611	569	546	523	822	778

*Calculated by approved IES Method.

TABLE IV.

Room Index	Per Cent Reflectances Ceiling, Walls, Floor			Calculated Average Footcandles: Luminaire Photometered at 5 feet	Calculated Average Footcandles: Luminaire Photometered at 20 feet	Measured Average Footcandles
I	80	50	10	155.3	153.8	150.8
H	80	50	10	186.5	184.5	186.0

luminaires are mounted at a distance above the work plane equal to their own length or less. For luminaires mounted at greater heights, a photometric test distance of five times the luminaire length may be preferred.

The authors wish to thank Al Goetz and John Guy, who designed the steel work for the goniometer and W. H. Johnson, who furnished valuable advice.

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DISCUSSION

A. J. BIRKHOFF:* In the introduction the authors mention that photometric results should not be expressed in candlepower unless the test distance is of such a magnitude that the source under observation can be regarded as infinitely small; or reversing this statement, leave the source with finite dimensions and increase the distance *ad infinitum*. This and this alone should be the criterion, or the candlepower approach should be replaced by a flux method based on light densities of the luminaire aperture. If this assumed point criterion cannot be applied, due to definite dimensions of the luminaire as well as practical test limitations of the test distance, it is my opinion that the development of the equation which refers to Fig. 1 shows inconsistencies; namely, acknowledgment of a linear dimension of the source, practically ignoring the width of the source, but by the same token introducing surface element A with certain luminance B.

I believe that the two-dimensional approach should be a complete one, since it is an attempt to be practical as well as compromising about something which cannot be accomplished otherwise.

The greater part of the luminaire data presently in use reveals that the difference between the intensity distribution in several planes perpendicular to the aperture plane of the luminaire is extremely small; or the sources are so diffuse that the dominance of one dimension does not appear in the metered results. The nearly identical shape of these candlepower distributions indicates that if any finite dimensions are introduced, there should be at least two, or one should use the point source method and that famous infinitely small eight-foot by one-foot aperture.

The equipment and apparatus described is impressive and emphasizes the need for a revision of our thinking in the photometric approach to highly-loaded light sources with that unpredictable behavior, by now so well known.

I would like to comment on the comparison shown in Fig. 11 and the compiled data presented in Table I, where corrected and uncorrected photocells are compared. Having some sense of fair play, it does not do justice to the end result of a race to match two horses when one is crippled. It would be very interesting to see the same data compared using a corrected (or uncorrected) cell in both cases.

D. M. FINCH:* The problems of photometry of highly-loaded lamps are very well outlined in the paper. It is apparent that the highly-loaded lamps are best measured when maintained in their designed operating position.

After considering all of the problems of making photometric evaluations of large sources, I decided that a short test distance could be used to determine the efficiency of luminaires and to obtain the zonal flux distribution for the calculation of coefficients of utilization. The intensity distribution diagram and the average brightness curves can be adequately derived from the zonal flux measurements.

Theoretical analysis will show that the efficiency will be correctly evaluated at any test distance, provided that sufficient measurements are made to adequately determine all of the flux emitted from the luminaire and from the lamps. The receiver photocell must have a cosine and a C.I.E. color response and the interflections must be substantially zero within the test enclosure.

The coefficients of utilization calculated from the short test distance zonal flux measurements will differ slightly when compared with the values computed from the long test distance values. The differences generally occur in the third significant figure and are in the order of one per cent maximum. The short test distance calculated values have been found to agree very closely with measured values.

More data on other luminaires with varying distributions will soon be forthcoming from the University of California laboratories in Berkeley. Preliminary data show excellent

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agreement in the efficiency measurements, as expected.

It is hoped that more photometrists will try the short test distance method and that this simplified procedure can be adopted in the near future.

R. L. SMITH:* The authors have developed a photometer possessing mechanical and optical nicety. The feature of being able to vary D/L is desirable especially for research problems such as those described.

The correction curves in Fig. 3 are all for $z_o = 0$. Curves for other values of z_o would be interesting and helpful. I do not have access to the original paper of Yamanouti. However, when using values of z_o not equal to zero, I obtain unreasonable values of C, indicating that typographical errors are present in the formula. The Yamanouti cylinder does not resemble lighting units for which I have theoretical and test data. Consequently, my comments are based on my own experience.

In testing an extended light source it is general practice to take candlepower readings at various vertical angles in a number of lateral planes to take care of the asymmetric character of the distribution. The average of these vertical planes is used in the calculation of the flux and output. If the test distance is D_1, this amounts to the same thing as surrounding the unit of maximum length L with a sphere of radius D_1. If the ratio of D_1/L is small, the distribution of candlepower on the inside of this sphere will be different from that on the inside of a sphere where D_2/L is large. However, the total flux on the inside surface of sphere of radius D_1 should be the same as that on the inside surface of sphere of radius D_2 if the other test variables such as temperature, voltage, etc., remain constant. The redistribution of candlepower may change the flux in the various 10-degree zones used for calculating the coefficients of utilization. The data given by the authors indicate that this redistribution of flux is not too great.

We have found in testing a one foot by four foot fluorescent unit at 10 feet and again at 25 feet that there is very little difference in the distribution of flux in the corresponding 10-degree zones even though a cosine corrected cell was not used at 10 feet.

In other words, the geometry is such that C factors vary above and below the 100 per cent values as the vertical and lateral angles change. With this compensating effect, if five or more planes are taken, the average candlepower curve at either D_1/L or D_2/L should give practically the same output.

For some time laboratory men have been concerned over the application of photometric data taken at larger distances than the mounting height above work plane found in the actual job. The authors' data tend to dispel this concern.

While the larger values of D/L may not be important for extended fluorescent sources, as pointed out by the authors, there are places for the larger values in testing of street or floodlighting equipment where the accurate measurement of angle and candlepower at that angle are required.

E. H. SALTER:** I have seen and have been duly impressed by the authors' goniometer built to provide, under existing limitations of ceiling clearance, for the distribution photometry of luminaires in their normal burning position. This is a real accomplishment.

I am interested in the comparative data covering an IES test run with this equipment and a test run under the proposed test conditions submitted by Professor Finch to the IES Testing Procedures Committee. It is not unexpected that the candlepower distribution curves are somewhat different, since in the latter case "apparent candlepower" is obtained as against "true candlepower" in the IES test. There is, however, no reason why the luminaire efficiencies should be different in the two cases, other than that the two tests were made by different procedures. After all, efficiency should be a fixed quantity except for measurement errors and differences in luminaire assembly between the two tests.

When the results of these two tests are used to compute coefficients of utilization, the influence of differences in candlepower distribution (or zonal lumens) would be greatest for the small rooms (I and J rooms), whereas the influence of differences in efficiency would predominate in the large rooms (A and B rooms). When these coefficients of utilization are examined in this light, it is seen that there is no significant difference for the small rooms and that the ratio between coefficients for the two test conditions for the large rooms is essentially that of the ratio between efficiencies obtained from the two tests. Had the two tests yielded identical values of efficiency, the coefficients for the two conditions would have been essentially alike. Unless tests run at the shorter test distance will consistently yield higher values of efficiency than tests at the presently prescribed IES test distance, it would appear that data from the proposed testing procedure will yield coefficients of utilization that are identical with the established testing procedures.

PHELPS MEAKER:* There has been considerable concern among photometrists over the problems of measuring these heavily-loaded lamps. As in the authors' case, lack of sufficient height in the photometer room has been the main difficulty. It just has to be done with mirrors. The authors' solution is most ingenious, and appears to conform to the requirements they have listed.

The effects of lamp operating temperature, drafts, and movements of the lamp about its axes all have to do with the amount of mercury in the arc stream, hence the mercury vapor pressure, arc watts and light output. Lest users become alarmed at the complexity of this combination of factors, it needs to be mentioned that the resulting change in light output will probably not exceed 5 per cent under any ordinary indoor operating conditions. As for lamps with non-circular cross section, changes in mercury pressure result in corresponding changes in arc voltage and wattage, so that if the light output goes down, the power consumed has decreased likewise, and lamp efficiency is substantially unaltered.

The changes in light output, therefore, are of concern chiefly to the laboratory responsible for accurate measurements of the amount of light.

Laboratory people who are interested should be aware that initial stabilization is not a matter of so many hours of burning, but rather a process of watching the output until it reaches stability. It would be good if the 200 hours of seasoning were performed with lamps in the horizontal position in which they are to be used in the laboratory.

The authors emphasize that the goniometer should move smoothly and steadily so that the translation of the lamps and luminaire will be effected without disturbing the distribution of mercury in the lamp. An engineer who assisted in preparing this discussion felt that it should be mentioned that this refers to a freely suspended luminaire, always hanging in the usual operating position. If a lamp is

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rotated about any horizontal axis, even a slow and uniform motion will still tend to cause displacement of the mercury and a change in light output.

Since each of the authors' mirrors handles light from one half of the lamp and luminaire, some readers might conclude that the test distance might be only five times four feet, or twenty feet. Actually, each mirror performs as half of a larger mirror viewing the entire luminaire, whose full length will govern the test distance.

The arguments at the beginning and end of the paper again emphasize that candlepower, as used in most photometric operations, is just a tool employed in computations, and rarely has much reality. In photometry, one measures illumination only, then converts it into candlepower so that someone else may change it back to illumination. Discrepancies in candlepower values are of concern principally in point-by-point illumination determinations. If one wants lumens in zones for evaluation of performance or output, however, he can be reassured that this is derived directly from the initial photometric measurement of illumination. It seems to me that the differences resulting from photometry at short distances may cause a shift of lumens from one zone to another. Do not be alarmed that any light will get lost! The authors' comparison of utilization tables shows that such shifts of light flux between zones has a small effect upon the utilization.

E. H. WITTE:* The authors should be thanked for including mathematical background helpful in explaining why photometry of four-foot and eight-foot luminaires of the same cross section often yields perplexing efficiency figures.

The goniometer described is certainly an ingenious solution to a common problem. While this photometer was designed to meet the difficulties imposed by heavily-loaded lamps, it also eliminates many of the nuisance factors which are present in the photometry of any fluorescent luminaire.

While the dimensions are not given, it would appear that the luminaire travels the circumference of a circle approximately ten feet in diameter. No doubt this is a continuous movement to permit automatic recording of candlepower. Are the air currents set up by this motion enough to appreciably change the output of 1500-ma lamps? It would be interesting to know what degree of change might be expected between a "stabilized" nadir reading and a nadir reading immediately after a 360-degree traverse, especially with a luminaire having little or no ventilation.

The authors' comments on the use of an integrating sphere for use with non-circular cross section lamps are helpful but why is direct photometry preferred? If the sphere is to be used for the lamps anyway, why not also measure the output of the lamp and luminaire? Thus, an efficiency figure is established and distribution curves need be run only for curve shape — no further calibration is necessary.

A comparison of the coefficients of utilization data shown in Tables II and III shows only three instances where the variation is appreciably greater than two per cent and a misprint or an arithmetical error seems probable in each of the three. This degree of precision would normally be acceptable, especially considering the accuracy of other items, such as the maintenance factor, used with coefficients of utilization. It should be pointed out, however, that the agreement shown is partly a happy accident due to the distribution of the particular luminaire tested. A comparison of the data shown in Table I shows that the shortened test distance results in a minus error at nadir and 85 degrees, a maximum plus error (about 12 per cent) within 35 degrees above and below horizontal and a return to a minus error directly overhead. All of these errors tend to cancel each other out so far as total efficiency and coefficients of utilization are concerned. With a luminaire having more output at higher angles, the errors would not be self-cancelling and the shortened test distance would result in greater errors. Further, since average brightnesses are calculated from candlepower, the brightness data would show the greatest error in the glare zone where accuracy would be the most desirable.

Further comparisons of this sort would be helpful in determining whether a shortened test distance can be justified.

R. D. BRADLEY:* I was aware that work was being done on this "ferris wheel" photometer and feel that the authors have made a major contribution. The problems they faced are not unusual and although one may have a 40-foot laboratory available, the question of burning stability of the source is always important and often acute.

I can readily visualize from the photographs how the mechanical arrangement works with the luminaire mounted along the long axis of the cage. There is a point which is not too clear, however, and that is as to how the 45-degree and parallel planes are arranged. Apparently, there is room enough to swing the luminaire at 90 degrees to the long axis of the cage, although this is not clear.

The authors' check points by three methods are interesting, particularly in that the variations shown are all within the repeatability limits of this type of photometry (± 2 per cent).

I have experienced instability of EHO lamps of the T-12 variety when trying to use them burned in vertical and 45-degree positions. The T-17 asymmetric lamps do not have this characteristic to such a marked degree. With the latter, shift is slow enough so that the 45-degree and vertical planes can be run without appreciable error where these runs only require 30 to 45 seconds (after recalibration of recording instruments).

The Yamanouti Correction is one very seldom used in practice; however, the authors show the possibility of discrepancies for four-foot vs eight-foot versions of the same luminaire. It should be borne in mind that a great many luminaires do not possess the cosine distribution assumed by Yamanouti, but depart quite widely from this assumption. It would be interesting to see what departures were encountered with such typical distributions as those found for the 25 per cent and up indust-ial unit.

B. F. JONES:** The authors are to be commended on their design, which should serve for the testing of luminaires using any fluorescent source. This design should be carefully considered by anyone faced with the problem of building luminaire test facilities for highly-loaded lamps.

One point in connection with this design should be made. While it is not necessary that the two cells receive equal illumination during the test, it *is* necessary that the two cells be of equal sensitivity. Otherwise, an error will result which is proportional to the ratio of the illumination on the two cells and to the ratio of their sensitivities. I would suggest that the cells be matched for sensitivity within perhaps two per cent or better, and that they be checked for match at intervals.

In connection with testing at the usual "five times" distances, it should be noted that other shapes than circular cylinders will show similar correction curves to those in

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Fig. 3. This indicates that when the length-to-width ratio of a luminaire is less than about 4:1, important errors may result even at a five-times test distance. However, if the equipment is calibrated with the bare lamps in the same pattern as they occupy in the luminaire, the same error will be present in the calibration, and will therefore be canceled to a large extent. It is for this reason, for example, that it has been possible to run accurate curves on four-by-eight-foot luminaires at 40-foot test distances. If, however, the equipment is calibrated one lamp at a time, this error may not be canceled, and can be of major importance.

The system of short-distance photometry submitted by Professor Finch shows great promise, and may well become the standard testing method once the industry is sufficiently educated concerning the actual meaning and worth of a candlepower curve. The present shortcoming of the system is that it requires complete distribution data on the bare lamps at the selected test distance, as well as on the luminaire itself. There seems to be no reason, however, why a lumen/apparent candlepower ratio could not be determined for this distance, and used to calibrate the equipment without running a complete set of curves on each lamp.

One difficulty in testing highly-loaded luminaires by conventional means or by either of the two methods described has been the time consumed in calibration of the T-17 grooved lamps. I have recently proposed to the Testing Procedures Committee of the IES a fairly rapid method of performing this calibration which, if it proves satisfactory, will reduce the time and labor necessary to test such luminaires. It also makes more practical the use of conventional testing equipment and procedures in testing such luminaires, with the result that laboratories can use their existing equipment even though it requires rotating the luminaire out of its normal burning position. By use of the calibration-point technique, the change in light output of the unit in the various burning positions ceases to be a problem, since all that is required is for the light output to remain constant during the time required to run each plane.

In the case of the 1500-ma lamps, however, this technique does require restabilization of the lamps before each calibration (once per luminaire test). This is necessary because tilting of the lamps during running of the distribution curve planes will usually displace the mercury from its "stabilized" spot. The Electrical Testing Laboratories in New York have found that the lamps can be restabilized in about two hours by wrapping insulation about them, to force the mercury to migrate more rapidly.

By a suitable combination of the techniques mentioned above, it is possible to obtain accurate tests on 1500-ma luminaires by means of conventional photometric equipment. The authors' photometer, however, is more elegant for the purpose. It will be more readily operated by personnel less sophisticated in photometry, and will require less time to produce results.

G. A. Horton, R. R. French and J. B. Arens:* Referring to Mr. Birkhoff's remarks about Fig. 1, we wish to point out that the same mathematical analysis would apply even if the source were a luminous disc instead of a line. With regard to Fig. 11, if an eight-foot luminaire is photometered at a distance of 10 feet, the half-angle subtended by the luminaire at the photocell is of the order of 22 degrees. Fig. 11 shows that the difference of response between cosine corrected and uncorrected photocells is quite small and should not make much difference in test results.

Professor Finch's remarks with regard to the short test distance method of testing are greatly appreciated and we will be happy to see the results of his forthcoming data on other luminaires with various light distributions.

With reference to Mr. Smith's remarks, we highly recommend the Yamanouti paper, as the various formulas are quite general and apply not only to cylinders but also to point source, line source, circular arc, disc, sphere, and rectangular plate which might simulate a troffer with flat bottom closure. The paper is somewhat difficult to obtain, but two sources we know of are the Library of Congress in Washington, D. C., and the Engineering Societies Library in New York City.

Mr. Smith is quite right about the formula being in error, as the s_o term in the denominator should be s_o^2; the exponent apparently got lost somewhere along the line. He is also correct that calculated efficiencies for the same unit should be the same regardless of photometric test distance.

We are essentially in agreement with Mr. Salter's remarks.

We are glad to know from Mr. Meaker that changes in light output of EHO lamps of non-circular cross section operating under ordinary indoor conditions will probably not be more than five per cent.

Mr. Meaker is quite correct in his statement that the optical system of the new goniometer does not change the geometrical requirements for so-called point source photometry where the recommended D/L is 5; that is, the distance of *each* photocell from the luminaire must be five times the maximum luminaire dimension.

In reply to Mr. Witte, the drawings for the new goniometer show the diameter of the circle traveled by the luminaire to be 110 inches. The rate of travel of the luminaire is 90 degrees per minute, or ¼ rpm, and this does not seem to change repeated nadir readings in excess of ± 2 per cent for all luminaires tested to date.

Our reasons for using direct photometry for EHO lamps of non-circular cross section are simply that the equipment is available, and if distribution curves are run on the lamps there is of course some small blocking of upward light from the lamp due to the supporting bar on the goniometer.

We do not believe that there are any errors involved other than those associated with normal experimental error encountered in photometrical measurements, and that the candlepower distributions obtained at short test distances are what are to be expected. As Mr. Witte mentions, it is the average brightness values calculated from the candlepower data which will be affected and a decision will have to be made as to whether or not data calculated in this manner will be acceptable.

In reference to Mr. Bradley's remarks, clearances within the space available for the new goniometer were quite acute, but by placing the cage near one wall of the photometer room there was enough space left on the other side to rotate the eight-foot luminaires horizontally about the vertical axis in order to obtain complete photometric exploration. This, of course, means that the cage can rotate vertically only 180 degrees from nadir to zenith rather than 360 degrees.

We have also experienced more instability with EHO lamps of circular cross section than with those of non-circular cross section.

The authors essentially agree with Mr. Jones's remarks concerning the matter of matching the photocells. Our photocell supplier was paid a considerable bonus for carefully selecting and matching the cells used in the new photometer. We also found the photometry by conventional methods of luminaires utilizing EHO lamps of non-circular cross section to be fairly satisfactory, but for lamps of circular cross section the results were unsatisfactory.

*Authors.

Photometry of

Low-Mounted Linear Sources

By DOMINA EBERLE SPENCER
C. EDWARD KOWALSKI

PRESENT outdoor lighting techniques specify luminaire characteristics in terms of candlepower, but candlepower curves are useful only if the illuminated surface is perfectly diffusing and is at a great distance from the source. For many applications, the illuminated surfaces are too close for the inverse-square relation to hold and are imperfectly diffusing. Candlepower specification in such cases is essentially meaningless.

In outdoor lighting studies, the photometric specification of the luminaire should be sufficient to provide complete information on:

(a) Appearance of perfectly diffusing surfaces,
(b) Appearance of imperfectly diffusing surfaces,
(c) Visual effect of luminaires.

Candlepower is a satisfactory concept for the calculation of the appearance of perfectly diffusing surfaces—if they are kept sufficiently distant from the light source. If the luminaires are very long and are mounted close to the ground, however, the appearance of even a perfectly diffusing pavement cannot be calculated from a single candlepower curve.

Actually, most of the surfaces to be illuminated outdoors are not perfectly diffusing. Dry pavements are themselves quite glossy. As pointed out by Spencer and Peek,[1] errors of several hundred per cent can readily be introduced if dry pavements illuminated by low-mounted fluorescent luminaires are regarded as perfectly diffusing surfaces. For wet pavements, still larger discrepancies are to be expected. It is hoped that the work of Finch[2] and others[3] will eventually culminate in an adequate specification of the reflecting characteristics of imperfectly diffusing surfaces. When such data are available, a candlepower specification of the luminaire will not permit the appearance of the surfaces to be calculated. One must know how bright the source of light appears from any direction, as well as the solid angle subtended.

Important for the future development of quality in outdoor lighting is a specification of the visual effect of the non-uniform surround. Rex[4] has recently applied both comfort and visual acuity data to the analysis of nighttime driving conditions. The comfort approach has been developed from the experimental work[5] of Guth, Putnam, and others. Blackwell[6] has also applied his research to outdoor lighting conditions. The relative visibility (delos)[7] approach has been used[1] for visual conditions on runway and turnpike. Irrespective of how the visual effect is analyzed, it cannot be based on a single candlepower curve. What the eye sees is not candlepower. Visually significant photometric specifications are needed.

This paper studies the photic field of a low-mounted fluorescent luminaire and develops a simple yet visually significant method of defining it. There is hope that the method suggested here may be extended to a large family of outdoor luminaires. A minimal set of laboratory measurements are suggested. The ways in which the simple concept of candlepower may be usefully employed are also considered.

Looking at the Luminaire

The cross-section of the four-foot fluorescent luminaire selected for analysis is shown in Fig. 1. It contains a 60-degree aperture lamp[8] whose open-

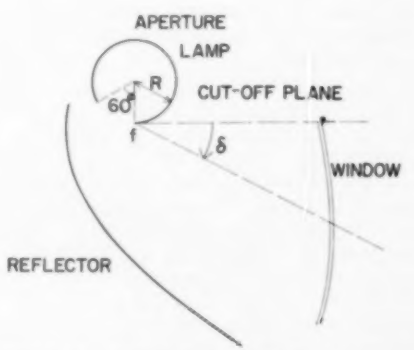


Figure 1. Cross section of fluorescent luminaire.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHORS: University of Connecticut, Storrs, Conn., and Sylvania Electric Products Inc., Salem, Mass. Accepted by the Papers Committee as a Transaction of the IES.

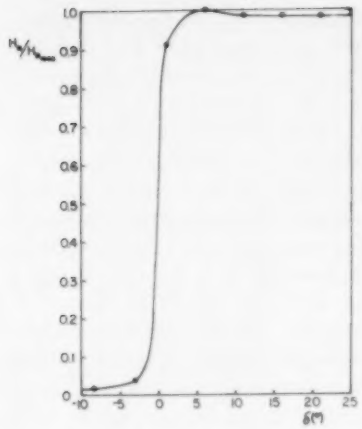
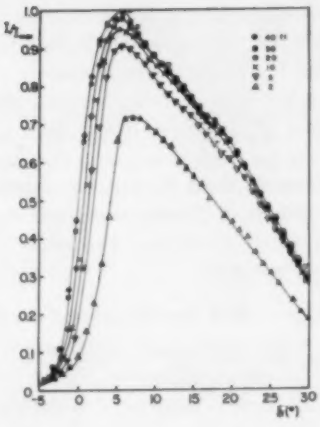


Figure 2 (left). $H_B H_{B_{max}}$ **for the center of the reflector as a function of angle** δ **below cut-off plane.**

Figure 3 (right). Family of vertical candlepower distributions measured at various distances.



ing faces toward a reflector. The major part of the reflector consists of a parabolic cylinder whose focus is placed at the lower edge of the aperture. The axis of the parabola is horizontal as shown in Fig. 1. A beam of light from the aperture will be reflected with its upper edge parallel to the theoretical cut-off plane. If there were no stray light and the reflector were perfectly specular, the reflector would appear black from any point above the cut-off plane. When viewed from below the cut-off plane, an image of the aperture will be seen and this image is nearly as bright as the aperture itself. As the angle δ below the cut-off plane is increased, the width of this image first increases rapidly and then decreases gradually.

It will be convenient to define the *cut-off region* as the space between the cut-off plane and the plane parallel to the cut-off plane which passes through the bottom edge of the window. It has previously been pointed out[8] that below the cut-off region the height of the aperture image is theoretically a function of δ alone, while in the cut-off region it also depends on the distance at which the luminaire is viewed.

The actual variation of helios H_B (brightness, if defined in terms of a converging lighteone) with angle δ is shown in Fig. 2. All measurements were taken with a Pritchard meter using a field of view of 0.1 degree. A point at the center of the reflector was selected and was viewed at various angles δ. Theoretically, the curve should be zero for negative values of δ and 1.00 for positive values of δ, rising with infinite slope at the origin. Actually, the curve drops to two per cent of maximum five degrees above the theoretical cut-off plane and has attained maximum five degrees below the cut-off plane. At 2.5 degrees above the cut-off plane, the value is four per cent of maximum; while at 2.5 degrees below, it is 96 per cent of maximum. Still sharper cut-off could be attained if stray light were further reduced and a more perfectly specular reflector were employed.

Illumination from the Luminaire

Analysis of the photic field of the luminaire requires measurements of the illumination as a function of δ at various distances l from the luminaire. The reference point, with respect to which l is measured, was taken at the lower edge of the aperture of the lamp and midway between the ends of the luminaire. Measurements were made at $l =$ 2 feet, 5 feet, 10 feet, 20 feet, 30 feet, and 40 feet.

It is well known that candlepower is defined, in an exact sense, only for a point source. In an operational sense, however, apparent candlepower may be defined at any distance by measuring the magnitude of the radial component of the D vector (lumens per unit area received at the point) and multiplying by the square of the distance. In this way apparent candlepower, with respect to an arbitrarily chosen "center" of the luminaire, may be defined at all distances for any luminaire, no matter how large. This apparent candlepower will not be a constant but can be expected to vary with distance.

Fig. 3 shows relative candlepower I/I_{max} as a function of distance l and angle δ for the vertical distribution in the plane perpendicular to the cut-off plane. The candlepower curves at 30 and 40 feet are practically indistinguishable, but at 20 feet, the peak value has fallen by two per cent, at 10 feet by five per cent, at 5 feet by nine per cent and at 2 feet by 29 per cent. These discrepancies occur for the vertical candlepower distribution on the plane of symmetry. Much larger discrepancies occur in the lateral distribution.

Thus, we can conclude that a single vertical candlepower curve will specify the illumination to within two per cent only at distances of 20 feet or more. If the luminaire is mounted 2 feet from the

pavement and is being used to floodlight a roadway 30 feet wide, a single candlepower curve will specify illumination correctly in the most distant traffic lane, but becomes significantly in error in two of the three lanes. Isolux curves based on a single candlepower curve will exhibit poorer uniformity than is actually obtained. Accurate predictions of illumination can be made, however, if a family of vertical and lateral candlepower curves is employed.

Equivalent Rectangular Source

The traditional specification of a luminaire by a single candlepower curve has the advantage of simplicity. Some of this simplicity can be retained if the fluorescent luminaire is specified by an equivalent rectangular source whose height and width may be functions of angle.

Fig. 4 shows the luminaire and its equivalent rectangular source. For convenience, the dimensions h and w are measured in a plane perpendicular to the direction in which l is measured. Then from the well-known rectangular source equations,[9] the value of D from a known rectangle of helios H_R is

$$\frac{D}{H_R} = \frac{1}{\pi}\left[\frac{h}{\sqrt{l^2+h^2}}\tan^{-1}\frac{w}{\sqrt{l^2+h^2}} + \frac{w}{\sqrt{w^2+l^2}}\tan^{-1}\frac{h}{\sqrt{w^2+l^2}}\right]. \qquad (1)$$

This equation applies to the vertical distribution in the plane of symmetry.

From laboratory measurements, D and l are found. The width w of the image of the aperture as viewed from the plane of symmetry was measured at 20.6 inches. If H_R is taken as a constant, $H_R = H_{Rmax}$, then the effective height h can be calculated from Equation (1). To facilitate calculations, an IBM 650 was employed. The problem of computer programming is discussed elsewhere.[10]

Fig. 5 shows the effective height of the equivalent rectangular source as a function of δ. The ordinate is expressed as h/R, where R is the radius of the lamp. In this example, $R = 0.75$ inch. The resulting curves become identical below the cut-off region, as predicted theoretically.[8] From the family of candlepower curves of Fig. 3, a single curve of effective height has been obtained. Use of a single curve to identify the luminaire characteristics in the region below cut-off is possible—if this is a curve of effective height of an equivalent rectangular source and is employed in conjunction with the standard rectangular source formula.[9]

Another interesting result is that the curve of h/R *vs* δ could be obtained from the standard candlepower measurements at 40 feet. Measurements at other distances are not needed to specify the illumination below the cut-off region. Similar procedures can be extended to lateral distributions.

The equations used to calculate D at points other than the plane of symmetry, but in the plane of maximum candlepower in the vertical direction are[9]

$$\frac{D}{H_R} = \frac{1}{2\pi}\left[\left\{\frac{h}{\sqrt{l^2+h^2}}\left(\tan^{-1}\frac{w_1}{\sqrt{l^2+h^2}} + \tan^{-1}\frac{w_2}{\sqrt{l^2+h^2}}\right) + \frac{w_1}{\sqrt{(w_1)^2+l^2}}\tan^{-1}\frac{h}{\sqrt{(w_1)^2+l^2}} + \frac{w_2}{\sqrt{(w_2)^2+l^2}}\tan^{-1}\frac{h}{\sqrt{(w_2)^2+l^2}}\right\}\cos\psi + \left\{\tan^{-1}\frac{h}{l} - \frac{l}{\sqrt{(w_2)^2+l^2}}\tan^{-1}\frac{h}{\sqrt{(w_2)^2+l^2}}\right\}\sin\psi\right] \qquad (2a)$$

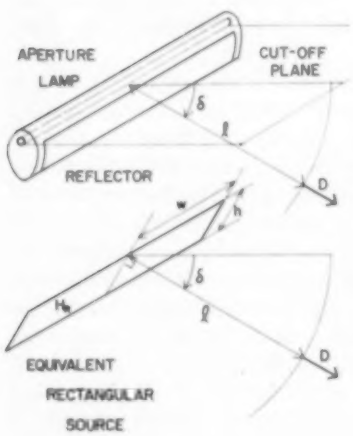


Figure 4 (left). An equivalent rectangular source.

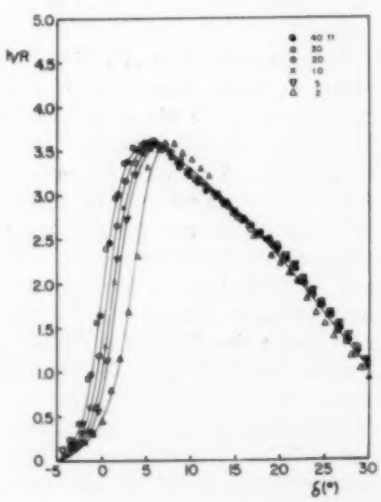


Figure 5 (right). Height of equivalent rectangular source as a function of angle δ below cut-off plane.

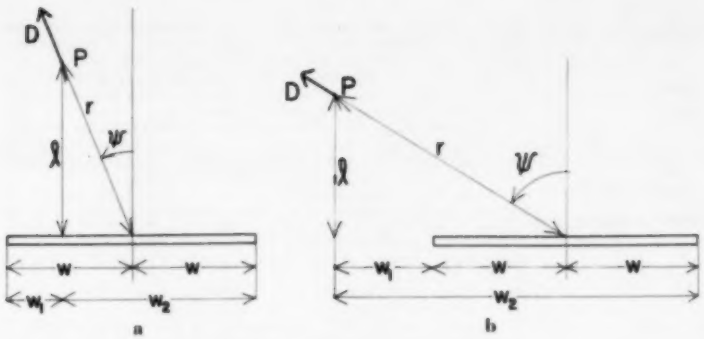


Figure 6. The widths of the equivalent rectangular sources: (a) If point *P* is opposite the luminaire; (b) If point *P* is beyond the end of the luminaire.

if the point P at which D is to be calculated is opposite the luminaire as shown in Fig. 6a and

$$\frac{D}{H_E} = \frac{1}{2\pi}\left[\left\{\frac{h}{\sqrt{l^2+h^2}}\tan^{-1}\frac{w_2}{\sqrt{l^2+h^2}} + \frac{w_2}{\sqrt{(w_2)^2+l^2}}\left\{\tan^{-1}\frac{h}{\sqrt{(w_2)^2+l^2}} - \frac{h}{\sqrt{l^2+h^2}}\tan^{-1}\frac{w_1}{\sqrt{l^2+h^2}} - \frac{w_1}{\sqrt{(w_1)^2+l^2}}\tan^{-1}\frac{h}{\sqrt{(w_1)^2+l^2}}\right\}\right\}\cos\psi + \left\{\frac{l}{\sqrt{(w_1)^2+l^2}}\tan^{-1}\frac{h}{\sqrt{(w_1)^2+l^2}} - \frac{l}{\sqrt{(w_2)^2+l^2}}\tan^{-1}\frac{h}{\sqrt{(w_2)^2+l^2}}\right\}\sin\psi\right] \quad (2b)$$

if the point P is beyond the end of the luminaire as shown in Fig. 6b.

Measurements of the lateral candlepower distribution were made at various distances from the luminaire in the plane of maximum vertical candlepower. These data are shown in Fig. 7 expressed relative to the values $I(0$ degrees) previously obtained in the plane of symmetry. The angle ψ is measured from the plane of symmetry as shown in Fig. 6. The maximum apparent candlepower occurs at $\psi = 50$ degrees and $l = 2$ feet. As ψ increases the discrepancy between the apparent candlepower as measured at 2 feet and at 40 feet increases. Beyond $\psi = 50$ degrees this discrepancy is always greater than 100 per cent.

By the use of Equation 2, the effective width of the luminaire was calculated as a function of angle. Whereas many curves are required to describe the lateral distribution of apparent candlepower, only one curve is required to represent the effective width as a function of angle. The maximum discrepancies from the single curve of Fig. 8 are about 10 per cent and are believed to be caused by inaccuracies in the experimental data rather than by inherent difficulties with the method of analysis. The shape of the curve of effective width as a function of angle is caused by the effect of the specular endcaps employed in the luminaire (Fig. 4). For small values of ψ these serve to slightly increase the effective length of the light source above its value on the axis of symmetry, but for large values of ψ, the endcaps serve as louvers and sharply reduce the effective width.

By the use of the familiar rectangular source equations[9] and the curves of effective height (Fig. 5) and effective width (Fig. 8) it is possible to cal-

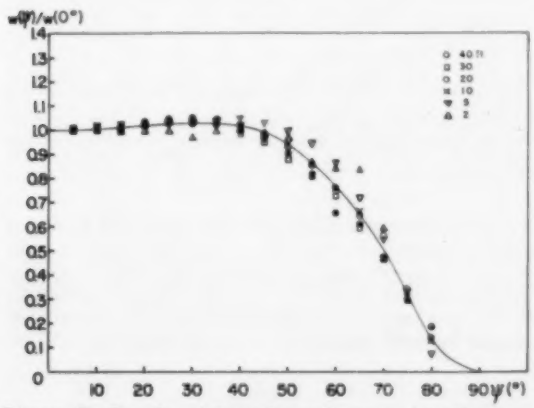


Figure 7. Family of lateral candlepower distributions measured at various distances.

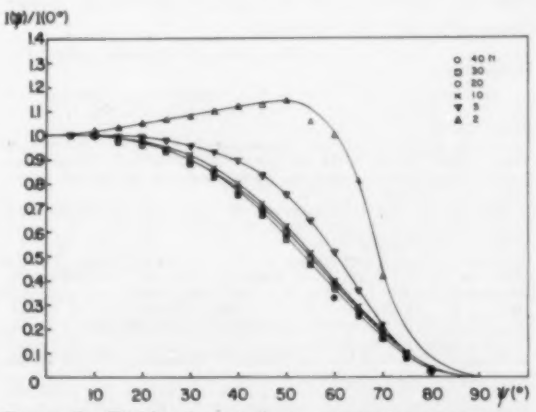


Figure 8. Width of equivalent rectangular source as a function of lateral angle ψ from plane of symmetry.

culate the $\boldsymbol{D}$ vector at any point. Combination of the information contained in Figs. 2, 5, and 8 also makes possible the calculation of the visual effect of the luminaires from any point of view.

Minimum Photometric Measurements

The type of fluorescent luminaire studied here can be completely specified by the following measurements:

(1) H_R as a function of angle,

(2) h and w as a function of angle,

(3) H_R as a function of temperature.

This specification has the advantage that the quantities measured are suitable for the long-range projects discussed in the introduction. The luminaire is specified sufficiently to permit the calculation of its effect on vision and to permit prediction of the appearance of actual pavement surfaces.

Only two types of photometers are needed: a meter to measure brightness (helios) of the reflector and a meter to measure lumens per unit area at 40 feet.

For the more restricted objective of calculating the appearance of perfectly diffusing surfaces, another type of specification may be preferred by some illuminating engineers:

(a) Vertical and lateral families of I/I_{max} as a function of angles and distance l.

(b) I_{max} as a function of temperature.

The families of curves required in (a) are readily calculated from the curves of effective height and effective width, but a family of apparent candlepower curves must replace a single candlepower curve if the concept of candlepower is to be used.

In conclusion, we wish to thank S. C. Peek of Sylvania Electric Products Inc., under whose direction the photometric laboratory for measuring low-mounted fluorescent luminaires has been planned and developed. We also wish to thank Knut Bouset and L. L. Montgomery of Sylvania Electric Products Inc. for aid in laboratory measurements and calculations.

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DISCUSSION

BILL F. JONES:* A great deal of the labor involved in calculating lighting levels, by the method described in this paper, can be avoided if it is recognized that the quantity in parentheses in Equation (1) is merely the shape factor from point D to the source—the same shape factor that is used so extensively in calculations with the luminous analog computer.[1] These shape factors have been calculated and made available in the form of charts and tables in NACA Technote 2836, "Radiant-Interchange Configuration Factors."[2] It would be wise for anyone contemplating the use of this method to obtain a copy of Technote 2836 which permits the calculation of the illumination on any plane at any distance from a luminaire of this sort, so long as the helios (brightness) and effective height and width of the rectangular source are known. The authors' Equation (1) is configuration P-1 in this publication.

If these luminaires are installed in a continuous row, of such length that they may be considered an infinite strip, calculation can be further simplified by the use of a shape-factor scale of the sort developed by Centeno and Zagustin, and illustrated in Reference 1 below. With the effective height of this strip known, the shape factor can be determined with this chart, and the illumination, therefrom, calculated by multiplying this factor by the source helios (brightness).

1. Jones, B. F.: "Use of Computers in Design and Analysis of Luminaires," ILLUMINATING ENGINEERING, Vol. LV, No. 7, p. 386 (July, 1960).
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D. E. SPENCER AND C. E. KOWALSKI:** We thank Mr. Jones for his constructive suggestions. It is gratifying to know that many people are interested in developing more convenient ways of employing the fundamental rectangular source equations. All of these will be useful in the development of more exact photometric procedures.

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Multilayer and Flexible Single-Layer Electroluminescent Lamps

By ROBERT J. BLAZEK
ROBERT W. WOLLENTIN
HANS B. BULLINGER

The development of methods and materials for the construction of flexible single-layer and rigid and flexible types of multilayer electroluminescent lamps is described in this paper. General objectives with respect to structural considerations, performance at normal and adverse environmental conditions, and specific problems encountered in the development of such lamps are outlined. Lamp construction and individual lamp components are discussed with emphasis on base materials, transparent conducting electrodes, lead-in conductors and methods of sealing lamp elements against moisture. Data on effects of scattering and absorption of light by individual layers of multilayer type lamps on brightness of individually operated emission layers are presented.

ELECTROLUMINESCENT lamps, because of their unique thin, wide area design and capability of light emission in all colors of the visible spectrum, have become a subject of increasingly wide interest.[1-12] The practical applications of electroluminescent lamps are presently limited, by virtue of the present status of low efficiency as a light source, to those areas of low level illumination such as instrument and panel lighting, read-out, night lights, indicators, displays, signs and a number of solid state devices where the electroluminescent lamp is one element of a structure in combination with ferroelectric or photoconductive materials.

In the past, the structure of the electroluminescent lamp has been generally restricted to a single-emission layer in a single-lamp unit. The possibility of superimposing a number of light emitting layers of various emission colors upon one another to form a multilayer lamp is of interest, not only from an academic, but also from a practical viewpoint. Such a lamp would find extensive application in instrument dial and panel lighting as well as other applications where space and weight saving features are of importance.

Since a good part of the investigative and developmental effort was supported by a government contract,[13] it was of prime importance to design the multilayer lamp to meet the MIL specified environmental conditions set forth in the contract.

The construction of the multilayer lamp on both rigid and flexible base materials required extensive effort especially in regard to the flexible lamp where prior experience was rather limited. Since much of the technology pertinent to the flexible multilayer lamp is common to the flexible single-layer lamp, a discussion is presented here of the latter type lamp. This is then followed by discussions of the multilayer flexible and rigid lamps.

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AUTHORS: Westinghouse Electric Corp., Bloomfield, N. J.

Flexible Single-Layer Lamps

The art of making flexible electroluminescent lamps, whether of the single-layer or multilayer type, is relatively new. Consequently, much effort was devoted to the development of flexible structures capable of meeting requirements as set forth in the contract. The effort included investigation of materials to be employed and fabrication techniques for constructing a single-layer lamp as well as determination of the resistance of the lamp to MIL Spec. The objectives were that the lamp withstand 500 flexing cycles over a ⅜-inch radius, high temperature, low temperature, high humidity, altitude and vibration conditions (as specified) with

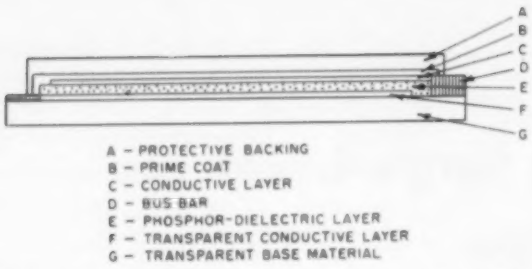


Figure 1. Schematic cross section of flexible single-layer lamp (drawing not to scale).

no damage to lamp elements. Other objectives were high initial lamp brightness and good maintenance of output at 115-volt and 400-cycle operation.

Of the various problems encountered in attaining flexible lamps that satisfy such objectives, three needed special effort for a satisfactory solution: (1) to develop a suitable transparent conductive coating, (2) to establish adequately sealed electrical contacts that prevent moisture ingress into the lamp and, (3) to provide sufficient protection of the lamp from adverse environmental conditions, in particular, high relative humidity, *e.g.*, 95 per cent R.H. at 71C.

Flexible Lamp Construction and Components

Generally speaking, lamps are prepared in the following steps:

(a) Vacuum deposition of a transparent conducting material (first electrode) onto the surface of the flexible transparent base material, such as plastic sheet which, if necessary, has previously been surface-treated chemically to obtain improved adhesion of the conductive coating to the surface.

(b) Covering all but a small portion of the first electrode with a layer composed of an electroluminescent phosphor embedded in a suitable plastic dielectric by means of a conventional spray technique. The uncoated portion of the first electrode provides for a bus bar type of contact.

(c) Evaporation of a conducting material on the phosphor-dielectric layer as under (a) with the bus bar properly masked, thereby forming a second electrode and bus bar type of contact.

(d) Application of a thin preliminiary protective coating (prime coat) by spraying and finally,

(e) Application of a moisture barrier backing material.

Fig. 1 represents a cross section of a single-layer flexible lamp constructed as outlined above. Total lamp thickness is primarily dependent on the thickness of the base and the backing material, selected on the basis of their individual flexibility, flexible quality imparted to the combined lamp structure and light transmission. The size and shape of the lamp may be arbitrarily chosen or adapted to the particular requirements of application.

This type of lamp structure may be made to emit light in two opposite directions if all materials employed are transparent or translucent; however, the second electrode generally consists of vacuum deposited opaque aluminum, which allows light to be emitted only through the opposite transparent conductive coating and substrate material. In multilayer-multicolor structures, of course, transparent interelectrodes would be utilized exclusively, and only the back electrode would be opaque and reflecting.

Serving as the base material, 0.005- to 0.01-inch-thick plastic films with low water vapor permeability have been used successfully. These included films of high density polyethylene, trifluoromonochloroethylene polymers and others which were employed successfully in electroluminescent lamp structures having stability over the temperature range of −54C to +85C.

The conductive films were deposited by standard vaporization or sputtering techniques in vacuum. The thickness of the films was controlled by discontinuing the vaporization at a critical d-c electrical resistance value as indicated by continuously monitoring the resistance of the film during its formation. The applied conductive coatings were then provided with bus bar materials, *e.g.*, silver paint, flashed aluminum or flexible silver-loaded epoxy resins. Various transparent conductive coating materials are applicable as electrodes. These include a number of metals such as: bismuth, indium, tin, gold, and gold alloy single-layers. Multiple metallic layers composed of combinations of gold and silver, silver and copper, and composite coatings of gold and various metal oxides are also usable. Relatively, best results in respect to light transmission and electrical resistivity are obtainable from composite gold and ferric oxide coatings. This type composite conductive coating was found to have about 10 per cent higher transmission than pure gold coatings with comparable electrical conductivities. Total light transmission of the gold-iron oxide coating plus plastic substrate (0.010-inch sheet of trifluoromonochloroethylene polymer) ranged from 66 to 71 per cent in the green spectral region with electrical resistivities ranging from 11 to 500 ohms per square. As bus bar type contact material, the flexible silver-loaded epoxy resin is most satisfactory on the basis of superior adhesion properties.

The application of electroformed flexible Ni-meshes may also be employed as the first electrode. The mesh is embedded in the surface of the plastic substrate by heat pressing. Lamps constructed

from the embedded optimum mesh size of 250 lines per inch which have about 80 per cent light transmission are lower in initial brightness compared to lamps incorporating evaporated gold electrodes on a similar composition base material. Several difficulties are associated with the use of metal mesh intermediate electrodes, in particular, an extreme tendency to wrinkle during handling is encountered which results in dark streaks due to the variations in dielectric thickness caused by the wrinkles and, at best, resultant lamp brightness is about 50 to 60 per cent of lamps employing the transparent conducting gold film electrode.

The next lamp components, the phosphor-dielectric layer, the second electrode, and the prime coat layer are less problematic. Several materials commonly employed in rigid electroluminescent structures are adaptable as the dielectric suspending medium in flexible lamps with major concern for satisfactory adhesion and flexibility. Both the phosphor-dielectric and prime coat layers are applied by conventional spray techniques. Some materials found to be particularly useful are silicone-alkyd varnish as the dielectric suspending medium and ethyl cellulose modified Canada Balsam as the prime coat. The prime coat serves as a means of protection for the thin aluminum back electrode against mechanical damage or attack from other materials used in the application of protective coatings, *e.g.*, epoxy and polyester resins.

Two basically different types of sealing methods may be employed to provide protection for flexible lamps against adverse environmental conditions, particularly high relative humidity:

(1) Providing protection by application of adequately flexible formulations of suitable epoxy resins over the lamp, as shown schematically in Fig. 1, or by using thin layers of similar resins to adhere additional flexible moisture barrier layers to the lamp. Barrier materials such as low water vapor transmitting film material were found to be useful. In Fig. 1, the protective backing then consists of two components, the barrier material and prime coat. The two-component protective system requires curing under heat and pressure at temperatures appropriate for the epoxy adhesive.

(2) A method employing heat sealing techniques. Here a moisture barrier layer, preferably of the same composition as the base material, is placed over the back of the lamp and heat-sealed around all edges with temperature-time schedules depending on the materials employed. This method requires a slight modification in lamp construction. While epoxy or epoxy/barrier layer protected lamps may be provided with open bus bars as shown in Fig. 1, heat-sealed lamps are provided with substrates extending beyond the bus bar and with lead-in conductors protruding through the seal line. Connection between bus bars and lead-in conductors is made by means of a flexible silver-loaded epoxy. Thin copper wires and, in the case of polyethylene base lamps, polyethylene coated 0.001-inch aluminum foil with the polyethylene stripped at both ends to provide for electrical contacts have been successfully employed as lead-in conductors.

Both types of seals, when appropriate materials were used, afforded comparable protection for flexible lamps operated at normal environmental conditions and 115 volts, 400 cycles for a period of about 1400 hours. In addition, lamps provided with either type of seal were capable of meeting several planned objectives, such as the high temperature test (lamps being maintained for 50 hours at 71C) and the low temperature test (lamps being maintained for 30 minutes at —54C) *i.e.*, lamp components were not affected by these temperatures. Distinctive differences in protective quality, however, were found when the lamps were operated at high relative humidity conditions, *e.g.*, 95 per cent R. H. Early failure during high humidity operation showed the complete inadequacy of the epoxy or epoxy/barrier layer seals for flexible lamps as indicated by rapid deterioration of the light-emitting layer due to moisture ingress. Within less than 48 hours the lamps became inoperable. In contrast, heat-sealed lamps are unaffected when maintained for 120 hours at 95 per cent R. H. with temperature cycling from room temperature to 71C to room temperature for five cycles. Heat-sealed barrier layer protection is, therefore, an important factor in providing flexible lamps with the desired resistance to high humidity operation.

Further improvement in lamp performance may be gained through the use of a flexible epoxy ad-

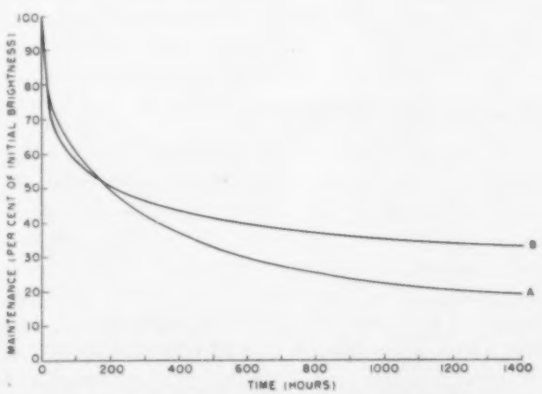


Figure 2. Maintenance characteristics of flexible single-layer lamps, green emitting phosphor, 115 volts, 400 cycles operation in normal environment.

hesive between the prime coat and the barrier layer before heat sealing. After the epoxy is fully cured under pressure, heat sealing is provided around the lamp edges. This method eliminates: (1) enclosure of an air pocket, which otherwise is automatically entrapped into the lamp during heat sealing and somewhat impairs flexibility characteristics and (2) enclosure of moisture which, if appreciable, deleteriously affects maintenance of output. Fig. 2 shows representative maintenance curves of epoxy/barrier layer protected flexible lamps (curve A) and heat-sealed epoxy filled flexible lamps (curve B) incorporating a green emitting phosphor, operated at 115 volts, 400 cycles in normal environment for 1400 hours.

Multilayer Electroluminescent Lamp Structures

Prior to the development of the present multilayer multicolor structure, an experimental type had been devised which was a composite structure of three relatively transparent individual lamps physically clamped together. The individual lamps were constructed of two sheets of electrically conductive glass, cemented together by a thin layer of a mixture of epoxy adhesive and phosphor. A thin sheet of a high electrical breakdown resistant transparent plastic was included to allow high voltage excitation.

In the multilayer design, it was desirable to build an electroluminescent lamp capable of independent emission in three colors, namely, red, blue and green and in combined emission to yield white light for operation at 115 volts, 400 cycles. Another objective was that each color be emitted from a six-by six-inch area with a 10 per cent maximum variation in brightness over the light emitting surface. High brightness, good maintenance characteristics, high electrical breakdown strength, acceptable resistance to MIL specified environmental conditions and a total lamp thickness of 0.075 inch also were desired.

Constructional Designs

In regard to the design and fabrication of the multicolor structures, effort was concentrated in those areas where the highest probability of success was believed to prevail for meeting the desired objectives in a minimum period of time. Consequently, little effort was applied to the development of a segmented multicolor structure of the type containing lines or dots of phosphors emitting in various colors from a single layer because of the unlikelihood of readily achieving lamps with the desired degree of uniformity. Instead, a multilayer type of multicolor structure was selected. This structure contained three superimposed emission layers composed of green, blue and red emitting phosphors embedded in plastic, separated by light transmitting electrically conductive films. Obviously, the amount of light transmission of the transparent electrodes and upper phosphor-dielectric layers are governing factors for the transmission of maximum light output from the lower emission layers for a given phosphor and constant dielectric thickness (voltage breakdown strength).

Intermediate Electrodes

In rigid multilayer structures four types of intermediate electrodes (light transmitting electrodes between phosphor layers) may be employed: (1) glass with a tin oxide type conductive coating, (2) electroformed metal mesh, (3) copper iodide and (4) evaporated gold films. The performance of the various types of electrodes is summarized below: *(1) Tin Oxide Coated Glass Electrodes*—The application of glass coated with conductive tin oxide imposes an immediate restriction on the ultimate thinness of the lamp structure dependent upon the thickness of the intermediate glass electrodes. Experimental models were made using glass, 0.014- and 0.022-inch-thick, with tin oxide coatings on both sides for intermediate electrodes and in thicknesses of 0.022 inch, 0.040 inch and 0.125 inch, with conductive coatings on one side only, as substrate.

The major problem in the application of tin oxide coated glass intermediate electrodes is to provide uniform dielectric thickness. This is especially complicated by the warpage of the thin conductively coated glass. The best approach to the solution of the uniform dielectric thickness problem appeared to be one whereby the phosphor-dielectric layer is formed first on one of the substrates and the second conductive glass electrode is applied by means of an adhesive with mild pressure to straighten the warped glass. This process requires an adhesive which is also a good dielectric material, since it becomes part of the total phosphor-dielectric layer. The adhesive must possess sufficient bonding strength to prevent relaxation of the straightened glass electrodes over the temperature range of —54C to +71C and be inactive chemically and physically with the phosphor-dielectric layer. It is also essential that the adhesive be solvent free, since any entrapped solvents would cause early loss of brightness during lamp operation. One further requirement is a low initial viscosity in the uncured adhesive to minimize the pressure required to eject excess material from the bond area. The epoxy resins possess most of the necessary qualifications and are most applicable. Some others which

may be used are adhesives based upon polyesters, acrylics, rubber base compounds and synthetic resins.

None of these materials, however, yield lamps of acceptable quality in the laminated glass electrode type structure. The use of epoxy resins generally result in excessive nonuniformity in the emitted light and, very often, shorting of the electrodes of the middle emission layer. While more success in preventing shorting accompanies the use of heat sensitive adhesives, nonuniformity of the emitted light is generally greater than in the case of epoxy adhesives. The nonuniformity is contributed to by the inclusion of air bubbles as well as the warpage of the glass. Thus, because of the difficulties encountered in regard to low electrical breakdown, electrode shorting and nonuniformity in light emission this design is not recommended.

(2) Metal Mesh Electrodes—The successful use of thin electroformed nickel mesh as the intermediate electrode requires special considerations of such variables as the type of adhesive to be used, dielectric thickness and phosphor concentration which are somewhat analogous to the glass electrode design described above. The utilization of 250 lines per inch, 0.0005-inch thick electroformed mesh provides optimum light transmission and brightness. A solvent type silicone adhesive used for applying the metal mesh and the application of a 1.5/1 phosphor to silicone-alkyd resin ratio in 0.0008-inch dry film thickness yields the optimum brightness, breakdown resistance and light transmission in the dielectric layer.

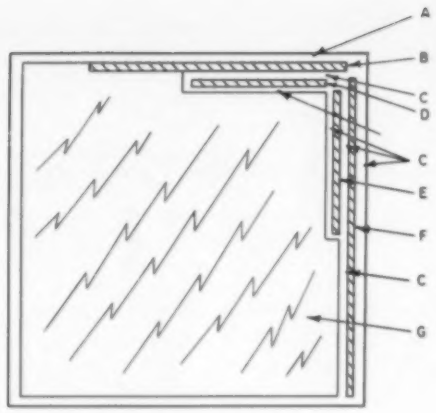
To form a multilayer structure, successive layers are constructed where each emission layer incorporates a phosphor of a different emission color and the metal mesh intermediate electrodes are common to two adjacent emission layers. Vacuum deposited aluminum is used as the back electrode. A typical lamp of this design might be one where a blue emission layer is foremost (to the viewer), a green emission layer is in the middle and a red emitting layer is in the back. The brightness of the layers at 115 volts, 400-cycles operation observed on experimental lamps of this design were of the order of: blue, 0.04 fL; green, 0.026 fL; and red, 0.006 fL. In addition to the low brightness, which were largely due to a distortion of the field distribution caused by the geometry of the mesh electrode, two types of nonuniformity of the emitted light occurred. One was attributed to the presence of wrinkles in the metal mesh and the other was caused by a "tenting" of the metal mesh when applied over small, raised irregularities in the phosphor-dielectric layer.

(3) Copper Iodide Electrodes—A multilayer structure may be prepared in which transparent conducting copper iodide is employed as the intermediate electrodes. In one model, three- by four-inch conductive tin oxide coated glass, without bus bars and with a resistivity of about 200 ohms per square was used as the substrate. The provision of alternated phosphor-dielectric and copper iodide films (by iodization of copper) completed the basic lamp structure. Considerable difficulty was experienced in early electrical failure of isolated portions of the copper iodide films or at the contact area between the bus bars and copper iodide films when the lamps were operated at 120 volts, 400 cycles. While uniformity and brightness are fairly good in this design, it is evident that the copper iodide intermediate electrode provides only limited application in multilayer lamps.

Table I—Transmission of Individual Phosphor-Dielectric Layers.

Color of El Source	Brightness of El Source (fL) 115 volts, 400 cycles	Per Cent Transmission Red Layer	Blue Layer	Green Layer
Green	5.5	58.2	77.3	61.8
Blue	2.4	61.4	86.4	69.5
Red	0.12	68.2	70.8	64.0

(4) Evaporated Gold Electrodes—The results of earlier work on evaporated gold electrodes in a single-layer flexible lamps indicated that composite conductive coatings, formed by the simultaneous vacuum deposition of gold with small quantities of iron oxide, afforded a more reliable film for use as intermediate electrodes in both rigid and flexible types of multilayer structures. Iron oxide modified gold films are relatively easy to prepare on glass and plastic substrates with electrical resistivities ranging from 15 to 80 ohms per square, capable of transmitting 60 to 70 per cent of the light emitted by a green source. However, considerably heavier gold coatings are required for intermediate electrode applications in multilayer structures, due to surface irregularities in the phosphor-dielectric layers. The surface irregularity effect was especially pronounced in the case of phosphor-dielectric layers upon flexible substrates. Unequal contraction between the silicone-alkyd binder and substrate during the curing cycles and/or flexing of the coated substrates frequently result in the formation of minute hair-line cracks in the phosphor-dielectric layers. This effect, coupled with the inherent roughness of the dielectric surface due to partially protruding phosphor particles, necessitates the deposition of relatively thick gold coatings. A light transmission ranging from 25 to 50 per cent is observed in the thicker gold-iron oxide



A – 0.125" SCORING AROUND 3 EDGES.
B – 0.063" x 5.75" EPOXY-SILVER BUS BAR TO GLASS ELECTRODE.
C – 0.063" SCORING.
D – 0.063" x 2.875" SILVER BUS BAR TO FIRST GOLD + IRON OXIDE ELECTRODE.
E – 0.063" x 2.875" EPOXY-SILVER BUS BAR TO SECOND GOLD + IRON OXIDE ELECTRODE.
F – 0.063" x 4.5" EPOXY-SILVER BUS BAR TO ALUMINUM ELECTRODE.
G – CONDUCTIVE COATING.

Figure 3. Bus bars and scoring for rigid multilayer lamp (drawing not to scale).

intermediate electrodes required for satisfactory lamp performance under continuous operation.

Transmission of Phosphor-Dielectric Layers

The light transmission of the individual phosphor-dielectric layers was determined for light of each of the three emission colors. Table I indicates relatively good transmission of the three emission colors through the individual phosphor-dielectric layers. Although the transmission of light emitted by the green and blue sources is lowest through the dielectric layer containing red phosphor, it is advisable, in the multilayer lamp design, to place the red emission layer on top of the lamp in order to conserve the inherent low brightness of the red emission. The arrangement of the blue emitting layer in the middle and the green emitting layer in the back is selected on the basis of the higher inherent brightness of the green emitting layer so as to provide a degree of nearly equal brightness from the various layers.

Constructional Details

Rigid Multilayer Lamps

Rigid multilayer lamps are constructed on a glass substrate 0.022 inch thick, one side of which is provided with a conductive tin oxide type coating having a resistivity of 300 ohms per square. The conductive glass surface is scored by sandblasting and epoxy-silver bus bars are provided as in Fig. 3. The arrangement of bus bars is designed to allow wide area contact to the conducting layers and to confine the exit of lead-in conductors to a minimum area. Nickel strips 0.002 inch thick, 0.062 inch wide and approximately 1.5 inch long are used as lead-in conductors. The metal strips are joined to the bus bars by means of conducting epoxy-silver paint.

The phosphor-dielectric layers are formed by the spray application of a phosphor suspension in a silicone-alkyd resin solution in a 1.5 to 1 phosphor-to-plastic ratio. An additional coat of clear silicone-alkyd resin solution is then applied in sufficient thickness to yield a dielectric breakdown strength in the cured layer in the range of 200 to 250 volts. The phosphor-dielectric coating extends 0.062 inch over the scored edges to prevent shorting of electrodes. The intermediate gold and aluminum back electrodes are deposited so as to extend over the appropriate bus bars and terminate 0.062 inch from the edges of the previous phosphor-dielectric layers. A cross-sectional drawing of the multiple structure is given in Fig. 4, where the prime coating and epoxy/aluminum protective backing are also indicated. The total thickness of the multilayer lamp is approximately 0.100 inch along the edges due to the overlap of the metal backing and 0.085 inch in the central area.

Flexible Multilayer Lamps

With the exception of substrate, protective backing and a few minor modifications, the flexible multilayer lamps were constructed similarly to the rigid lamp counterpart. A fluorocarbon polymer (polychlorotrifluoroethylene) extruded in sheet form in 0.010 inch thickness is advantageous as a flexible substrate, since it possesses a high degree

A – GLASS SUBSTRATE.
B – CONDUCTIVE COATING.
C – RED PHOSPHOR LAYER.
D – GOLD + IRON OXIDE ELECTRODE.
E – BLUE PHOSPHOR LAYER.
F – GREEN PHOSPHOR LAYER.
G – ALUMINUM ELECTRODE.
H – PRIME COATING.
I – EPOXY RESIN.
J – SILICONE-ALKYD CLEAR LAYER.
K – ALUMINUM SHEET.

Figure 4. Cross section of rigid multilayer lamp (drawing not to scale).

Table II—Brightness and Transmission of Flexible Lamp Layers.

Layer	Per Cent Transmission	Total Per Cent Transmission	Brightness 115 volts, 400 cycles (fL)
Plastic and gold coating	66.6	66.6	.....
Red phosphor-dielectric	45.9	30.6	0.03
Second gold coating	49.3	15.1	.....
Blue phosphor-dielectric	52.0	7.8	0.03
Third gold coating	33.4	2.6	.....
Green phosphor-dielectric	.....	.....	0.10

of clarity, flexibility, thermal stability, and moisture resistance. A transparent conductive coating of gold and iron oxide is deposited upon the surface of the plastic to provide the top electrode of the multilayer lamp. Alternated phosphor-dielectric layers of various emission colors and gold-iron oxide intermediate electrodes complete the basic lamp structure.

Lead-in conductors consist of 0.003-inch diameter bare copper wires which are joined by means of epoxy-silver adhesive to flexible conducting epoxy bus bars that were previously applied to the plastic substrate. Encapsulation of the lamps is afforded by sandwiching a layer of flexible epoxy resin between the lamp and an additional sheet of 0.010-inch thick fluorocarbon plastic. The laminate is thermally cured under mild pressure with the copper wire lead-in contacts projecting between the plastic sheets. After removal of extraneous flexible epoxy between the plastic sheets at the outer edges of the structure, the edges are heat sealed to provide maximum moisture protection. Copper prongs equipped with soldered external attached lead wires are applied to the contact areas with conducting epoxy adhesive and all junctions are coated with a resilient epoxy resin to electrically insulate exposed contacts and to increase the mechanical strength of the connections. The total thickness of the flexible multilayer structure is approximately 0.030 inch.

Transmission and Brightness

There is little difference in the light transmission and brightness of equivalent emitting layers of the rigid and flexible types of multilayer lamps. The results of measurements taken on a representative sample flexible structure after each successive layer was applied during construction are given in Table II.

Evidently, the relatively thick gold and iron oxide coatings required to prevent breakdown of the electrodes on lamp operation and the extra thickness of the dielectric layers to ensure a breakdown in excess of 200 volts, had the combined effect of low transmission through the layers with resultant loss in brightness through absorption. An additional factor contributing substantially to low brightnesses of the two uppermost layers is the substitution of the highly reflecting electrode by the transparent electrode. The light emanating from a single phosphor-dielectric layer would normally be emitted equally from both surfaces of that layer. In a single-layer lamp structure where one surface is covered with a highly reflecting aluminized electrode, the light emitted in that direction is presumed to be largely reflected back through the phosphor-dielectric layer and emitted from the front surface except for the portion which becomes absorbed in transit. In multilayer structures, this situation prevails only for the bottom (green) layer which has one surface coated with aluminum. The middle (blue) and top (red) layers, however, do not have the advantage of the highly reflecting surface on one side; rather, their surfaces are coated with low reflecting coatings, thereby allowing the light emitted in the back direction to be transmitted into underlying layers of phosphor-dielectric and transparent conducting coatings. Such light will certainly be rather highly absorbed before being scattered or reflected back through the upper layers toward the viewer. Consequently, the brightness of the middle or top layer in a multilayer structure might be expected to be reduced by a factor of approximately one-half in addition to the absorptive losses incurred through the layers above the emitting sections.

A substantial improvement in brightness, perhaps in the order of factors of 2 or 3, might result from better control of the thickness of the phosphor-dielectric layer to allow deposition of conductive coatings with a higher degree of light transmission, and optimization of the phosphor to dielectric ratio so that such layers have maximum individual brightnesses consistent with maximum transmission of light generated from underlying layers. The extent to which these improvements may be realized can only be determined as a result of extensive efforts to optimize all factors and to develop degrees of control and reproducibility hitherto unknown in the fabrication of electroluminescent lamps.

Environmental Test Results

Evaluation tests of the rigid and flexible multilayer structures showed that their performances were essentially identical. No significant differences in the two types of lamps were evident with respect to their brightnesses, their ability to withstand high temperatures, and their high altitude performance. The rigid type lamp exhibited somewhat superior performance with respect to maintenance and ability to withstand high humidity operation;

the flexible type lamps displayed somewhat better performance with respect to their ability to withstand low temperatures and vibration. In general, both the rigid and flexible multilayer lamps withstood the environmental tests in the military specifications remarkably well.

Summary

Flexible single-layer electroluminescent lamps were prepared from plastic substrates for evaluation of materials and methods for protecting flexible structures against adverse environmental conditions and for determining the effects of the environmental tests on lamp components and characteristics. The results of this investigation set the basic groundwork for the fabrication of flexible multilayer lamps.

Rigid and flexible type multilayer structures were prepared which are capable of emitting red, blue, and green light and combinations thereof, from a single six- by six-inch area source. In regard to uniformity and brightness of the emitting layer, best results are obtained through the use of iron oxide modified gold intermediate electrodes vacuum deposited between successive phosphor-dielectric layers.

The two types of multilayer lamps were constructed from similar components except that the evaporated gold and iron oxide coated fluorocarbon plastic substrate in the flexible lamps replaced the conductively coated glass of the rigid lamp, and heat sealed fluorocarbon plastic sheet protective backing in the flexible lamp replaced the epoxied aluminum sheet backing utilized in the rigid lamp.

The performance of the rigid and flexible type lamps was remarkably similar and both types withstood adverse environmental tests exceptionally well.

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DISCUSSION

LUKE THORINGTON:* The authors undertook an admittedly tough job. Making a rigid single-layer electroluminescent lamp is one thing—making a flexible multilayer, multicolor lamp is quite another. Given the suggestion from the title, it is tempting to let one's imagination run to the day when lighting is purchased in rolls to be applied to interior walls much like wallpaper, with changes in hue and brightness controlled at will! The present state of the art as described in the paper, however, raises some very practical questions.

For example, the brightness levels given for red, blue, and green emission of the flexible multilayer lamp in Table II are in the range where human vision changes from photopic to scotopic.[1] As the latter does not sense hue and saturation differences, it seems logical to ask whether or not the different colors are actually visually distinguishable in this lamp; if not, then what function does the lamp serve? The question is especially pertinent if the brightnesses given were measured as the authors state that they were, *i.e.*, "after each successive layer was applied." This would seem to mean that the values for the green and blue layers would be further attenuated in a completed lamp by absorption by the overlying layers. With reference to the latter, would the authors state what they mean by transmission of the layers in Tables I and II? Is this meant to be luminous transmittance?

One of the primary objectives of the present study was to achieve a degree of flexibility such that the lamp would withstand 500 flexing cycles over a ⅜-inch radius. No mention was made by the authors of this objective being attained nor any other indication given of the degree of flexibility of completed lamps. How flexible are the lamps? Can they be flexed 500 times over a ⅜-inch radius—while burning?

It is noted that the order of phosphor layers in typical lamps using wire mesh electrodes is blue, green, and red, where blue is nearest the viewer. The authors then proceed to show by measurement why the order red, blue, and green is to be preferred. Would the authors reconcile this apparent contradiction?

Finally, the authors should be gently chided for omitting pertinent references, *viz.*, numbers 21, 22, and 23 cited by H. F. Ivey in "Problems and Progress in Electroluminescent Lamps."[2]

1. Committee on Colorimetry OSA: *The Science of Color*, page 105 Thomas Y. Crowell Co., New York.
2. Ivey, H. F.: "Problems and Progress in Electroluminescent Lamps," ILLUMINATING ENGINEERING, Vol. LV, No. 1, page 13 (January, 1960).

K. H. WEBER:** The authors refer to the newness of the art of making flexible electroluminescent lamps, and to the considerable efforts they have devoted to the development of such flexible light sources. Consequently it appears ap-

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propriate to point out that, as the authors themselves undoubtedly intended, this summary of their approach is not necessarily representative of the entire state of the art achieved with flexible electroluminescent lamps. Such lamps have, of course, already been developed to the point of commercial availability.

For example, electroluminescent lamps made within our own area of responsibility differ from those discussed here in materials, in structure, in manner of construction, and, not unnaturally, in the resulting properties. Perhaps the most notable of these differences is brightness at least two to five times greater than those quoted in this paper, for comparable conditions. Such developments, we believe, greatly extend the range of applicability of electroluminescence.

The authors emphasize the objectives of good maintenance, particularly at high relative humidity and high temperature. The representative maintenance data actually shown in Fig. 2 indicate a depreciation of 20 to 30 per cent in 1400 hours for their flexible lamps under "normal" environmental conditions. The authors state, in addition, that both their rigid and flexible lamps withstood adverse environmental tests exceptionally well. It would be a further contribution if the authors would indicate quantitatively how these maintenance data are modified for such extreme temperature and humidity conditions.

The authors' finding that composite gold and ferric oxide coatings are superior to gold alone seems to be a step forward in the area of evaporated, transparent conductive coatings. Will the authors comment on what preparation of the trifluoromonochloroethylene and phosphor matrix surfaces are made before deposition, and on such variables as substrate temperature, time, absolute pressure, and ratio of ferric oxide to gold?

Finally, given the characteristics of the single-color electroluminescent lamp, the authors have performed a worth-while service in demonstrating the properties that result from them for the multilayer, multicolor electroluminescent lamp.

K. H. Butler:* The possibilities of combining electroluminescent layers of different colors into a single structure have intrigued people ever since the first demonstration of electroluminescence before this Society in 1950. The authors of the present paper have set a higher goal in trying to make a flexible lamp with such a structure.

They have succeeded in combining the older techniques of evaporating metals to form an adherent light-transmitting coating on a plastic substrate, of embedding electroluminescent phosphors in organic dielectrics and of heat-sealing a barrier layer into a synthesis, resulting in a flexible multicolored lamp.

While the resulting product has some scientific interest, it is questionable, in view of the performance data, whether there is any practical value in such a complex assembly.

The multicolored lamp gives blue at 0.04 fL, green at 0.026 fL and red at 0.006 fL when operated at 115 volts, 400 cycles. This is low indeed when compared to the electroluminescent night lights now available commercially. The maintenance characteristics of Fig. 2, showing at least 60 per cent deterioration within 1000 hours, even in normal environment, is also far inferior to the values obtainable with ceramic dielectrics. Would the authors care to comment on future prospects of improved performance?

*Sylvania Electric Products Inc., Salem, Mass.

R. J. Blazek, R. W. Wollentin and H. B. Bullinger:* In response to Mr. Thorington, the authors acknowledge that the brightness levels of the emitting layers of the multilayer structure were much lower than originally anticipated. This was attributed primarily to the excessively high light absorption of the thicker phosphor-dielectric layers and intermediate electrodes required to provide adequate dielectric breakdown strength. However, the various emission colors are readily discernible at 120 volts, 240 cps operation. Some improvement in brightness may be realized through further optimization of the ratio of phosphor to dielectric to yield maximum light transmission and emission of each emission layer. Improvements in the smoothness of the surface of the phosphor-dielectric layers, *e.g.* by planishing, would enable the deposition of thinner, hence more transparent, intermediate electrodes.

In clarification of the tables, Table I presents luminous transmittance values for individual dielectric layers containing unexcited red-, blue-, and green-emitting phosphors, respectively. Electroluminescent lamps having essentially identical spectral energy distributions as the phosphors contained in the individual dielectric layers were employed as light sources. In Table II, the values presented in the "Per Cent Transmission" column were derived from the values given in the "Total Per Cent Transmission" column. The values contained in the latter column were obtained by measuring the transmittance of green light emitted by an electroluminescent source through the multiple layers formed by the successive applications of layers in the order stated in the "Layer" column. A photomultiplier assembly corrected for eye sensitivity was employed for all measurements; consequently, the values presented in Tables I and II are the luminous transmittance of the layers. There will be no further light attenuation of the lower emitting layers other than had been indicated because the total transmission was obtained from measurements on the combination of layers. The values derived therefrom take into account interreflection phenomena and associated absorptive losses between layers.

The flexible multilayer lamps withstood all the specified environmental tests and, in addition, 500 flexing cycles over a ⅝-inch radius, without delamination or other adverse effects on lamp performance. Although the lamps were not operated during this particular test, other empirical flexual tests have indicated that the lamps may be flexed while operating without detrimental effects.

During the early stages of the investigation on multilayer structures, which involved the evaluation of wire mesh intermediate electrodes, the preferred arrangement of the various emission layers had not been determined and, consequently, was arbitrarily chosen. In the preferred lamp design with composite gold and iron oxide electrodes, the various layers were placed in the order of increasing luminous efficiency toward the bottom (red on top, blue in the middle, and green at the bottom) to favor equalization of the brightness of the emitting layers at the specified operating parameters of 115 volts, 400 cps.

In reply to Mr. Weber, maintenance data taken on aluminum-backed rigid lamps and epoxy-filled, heat-sealed flexible lamps previously subjected to humidity cycling and high-temperature environments (71°C for 50 hours), generally indicated little or no increase in deterioration rates in comparison to equivalent control lamps which had not been subjected to the environmental tests.

*Authors.

The plastic substrates were thoroughly cleaned with ethanol prior to the deposition of transparent conductive coatings. Silver bus bars were applied either to the substrate or to a reference strip for monitoring the resistance of the metallic film during vapor deposition. The charge of gold and iron oxide was evaporated as rapidly as possible, generally within a few seconds, at a pressure of about 5×10^{-5} mm Hg (air being the residual gas). Although the composition of the composite gold films was not analyzed, it is probable that they contained from five to eight per cent by weight of ferric oxide. Further information on the deposition of thin metallic films on plastic substrates and phosphor-dielectric matrices is contained in the "Multicolor Electroluminescent Lamp" report.[1]

It is recognized by the authors that a number of references pertinent to many of the areas of electroluminescence touched upon in this presentation were omitted. This is at least partially justified on the basis that the available literature on electroluminescence is indeed extensive and complete reference listing would be most formidable. It was, therefore, the authors' intent to include only a selected few as being representative and to serve as an introduction to those areas touched upon. However, in the interest of further recognition and information, a list of additional references is presented.[2-10]

In response to Mr. Butler, recent advances in the technology of construction and materials employed in multilayer, multicolor structures have resulted in structures having very pronounced brightness increases; *e.g.*, in some instances as much as 15 fold over those values presented in the paper for the emitting layers. High brightness levels need not necessarily be requisite for determining the practicality of the multilayer multicolor structure since certain applications, such as indicating devices in aircraft panels, generally require relatively low brightness levels.

With new and improved phosphors under development, plastic dielectric lamps are foreseen which will have considerably better maintenance of output with considerably higher brightnesses than those disclosed in the paper.

No theoretical reason is presently known which would predict superior inherent maintenance performance for phosphors embedded in ceramic medium than for phosphors embedded in a plastic medium. Full realization of the inherent maintenance of a phosphor embedded in any medium is dependent upon the degree of protection against moisture afforded the phosphor. This is a greater problem in the case of the phosphor embedded in plastic but it need not necessarily be a limiting factor. In support of this theory, continuous progress in the direction of improved plastic embedding media and protective coatings has resulted in a steady increase in the length of useful life of the lamp. In regard to resistance to high humidity conditions, low temperature shock and temperature cycling, the performances are roughly comparable for phosphors embedded in ceramic and plastic mediums. On ambient operation, however, full potential operating life of either plastic or ceramic dielectric structures has not as yet been realized. Because of concentrated effort on the plastic embedded type lamp, progress has led to a performance equal to that for the ceramic embedded type. Both of the lamp types have shown nearly 3500 hours of operation to one-half of initial brightness for operation at 120 volts, 400 cycles per second. Inherent maintenance of the phosphor still is indicative of substantially longer life than these values attest to and it is foreseeable that one may soon begin to refer to electroluminescent lamp maintenance values of an order of magnitude similar to fluorescent lamp values.

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Fluorescent Lamps for Photo-Duplicating Service

By C. J. BERNIER

In modern offices and factories the reproduction of letters and documents is done principally by means of the light-copying process. With this method documents can be reproduced simply, cheaply and faultlessly. Light copying is based on two main types of processes, *i.e.*, photo-chemical and photo-electrostatic (Xerography). Fluorescent lamps designed specifically for use in photo-duplicating equipment using either process are the subject of this paper.

Because of their relatively small output, fluorescent lamps are not used where very high printing speeds are required. High pressure mercury lamps are used at poor efficiency in these brute force machines. However, recent advances in the development of light sensitive papers have drastically lowered the level of incident energy required for exposure (0.1 joule/cm², or less). The advent of high speed papers coupled with the development of very-high-output fluorescent lamps has opened up a widespread demand for simple, high efficiency machines with moderate printing speeds. The lamps develop little heat, so special cooling can often be dispensed with, and they come up to full efficiency at once.

Photo-Chemical Process

In this process the photo-type paper has a light sensitive layer which chemically decomposes when exposed to artificial light of proper spectral qualities. The paper is placed in contact with the original document in such a manner that the drawing or printing in the original prevents the light energy from reaching the sensitized layer. At the places where light does not reach the layer, chemical decomposition does not take place. During development, which follows exposure, the non-exposed parts turn color, the color depending upon the chemicals used. Exposed parts remain colorless.

Photo-chemical light-copying techniques can be grouped under two main headings. In printing by light transmission, where the facsimiles are taken from a translucent original, only one side of the original contains the drawing or printed matter. In reflex printing the facsimiles are taken from an original which can be opaque and which may contain a print or drawing on both sides. All papers conform to the reciprocal rule, that is, for exposure, the product of energy and time is a constant, provided that certain critical paper temperatures are not exceeded.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHOR: Sylvania Lighting Products Inc., Danvers, Mass. Accepted by the Papers Committee as a Transaction of the IES.

Printing by Light Transmission

The diazo process, a process where two azo compounds are used to produce coloring, is used almost exclusively for this type of light copying. The process can be wet or moist. Most diazo papers are sensitive to violet or ultraviolet radiation. This radiation occurs in daylight in such low intensity that work can be done with photo-type papers in daylight and in artificially lighted rooms without paper spoilage. Fig. 1 shows the spectral sensitivity of four typical diazo papers in common use today.

In designing a fluorescent lamp for optimum printing speed for a specific paper one simply attempts to match the peak spectral emissivity of the lamp with the peak spectral response of the

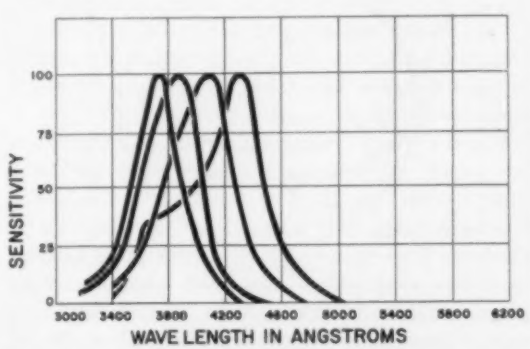

Figure 1. Spectral response of typical diazo papers.

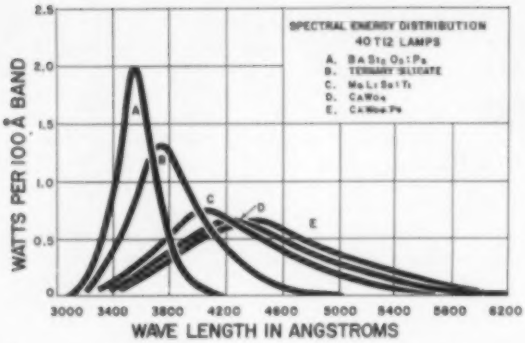

Figure 2. Spectral energy distribution of some 40-watt T12 diazo lamps.

paper. The peak emissivity of a fluorescent lamp is determined by the phosphor used. Some phosphors require the use of an activator material to give fluorescence. Others require no activator to cause the material to fluoresce but the peak emission wavelength can be shifted with the addition of some activator. Calcium tungstate phosphor requires no activator and will radiate with a peak wavelength of 4100A, as shown in Fig. 2. With lead as an activator the peak can be shifted to about 4400A. For the lower wavelengths, barium silicate, lead activated, has a peak emissivity at 3560A. Between these two regions are such phosphors as magnesium lithium antimonate, titanium activated, peaking at 3900A and a ternary silicate (magnesium, barium, strontium), manganese activated, peaking at 3750A. The curves in Fig. 2 are plotted in absolute energy units and values given are for the 40-watt T12 lamp.

The proper lamp to use for a given paper can be chosen by super-imposing the response curve of the paper onto the emissivity curve of the lamp in question and plotting the product of the two curves. If the ordinate for the lamp curve is plotted in absolute energy units and that for the paper in per cent units, the area under the product curve is a measure of the energy in watt-seconds absorbed by the paper, assuming that all the light energy from the lamp is incident on the paper. By applying a utilization factor for the machine involved, actual printing speed can be estimated.

Fig. 3 shows a product curve for a 40-watt diazo lamp (calcium tungstate, no lead) when used with diazo paper type D. The mercury line radiation has been taken into account in this diagram to show the importance of considering this radiation in design work. The lines have been arbitrarily given a width of 200A in order to give them area and reduce their heights to practical levels for plotting. From the curves it is seen that about 50 per cent of the light energy of the lamp is absorbed by the paper, 20 per cent of which comes from mercury line radiation alone. In many cases, the bandwidth (wavelength distance between the 50 per cent points) for papers is much less than that for lamps.

A common practice in light copying is overloading of fluorescent lamps to increase printing speeds. Since lamp life of 1000 hours or less is acceptable, lamp currents are often increased by 100 per cent or more over ratings. When this is done, mercury line radiation becomes a very important factor since, with increased loading of fluorescent lamps, the longer wavelength mercury line radiation (3655Å, 4047Å and 4358Å) does not saturate as rapidly as the 2537Å radiation, which excites the phosphor.

The extra-high-output T12 lamp is ideally suited for many machine types. With a loading of 25 watts per foot, the lamp produces about two and a half times the light energy of the 40-watt lamp at standard loading, and maintains uniform brightness throughout life. Lamp lengths from one and a half to 6 feet have been used. Mercury temperature can be controlled to obtain optimum efficiency either by using the temperature control chambers[2] built in the lamp or by means of cooling units built into the machine.

Reflex Printing

In this process light passes through the negative to the original and is reflected back to the sensi-

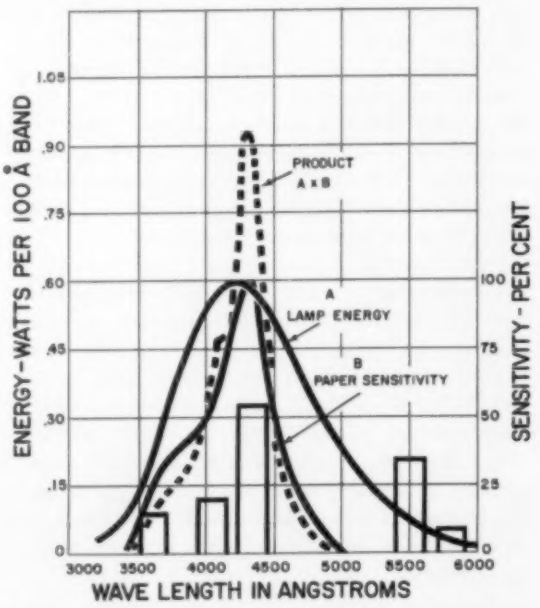

Figure 3. Determination of energy absorbed by diazo paper type D when exposed to light from a 40T12 diazo lamp containing calcium tungstate phosphor.

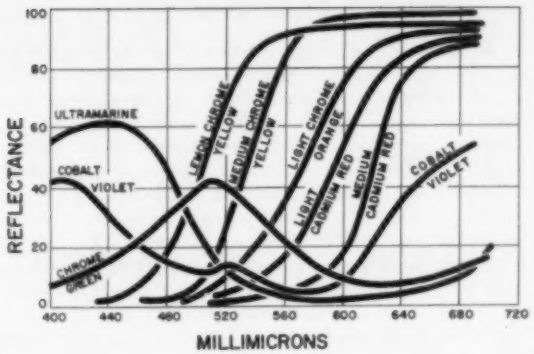

Figure 4. Spectral reflectance characteristics of some inorganic inks.

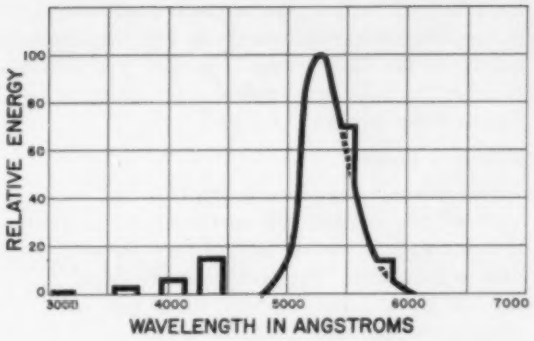

Figure 5. Spectral energy distribution of green fluorescent lamp using zinc ortho silicate phosphor.

tized surface of the negative. The exposed negative is then used to obtain a positive print on a sensitized copy paper. Unlike the diazo process, where black inks are generally used for drawings or printed matter, the reflex process is used to copy letters, circulars, book pages, etc., where a variety of ink colors are used. The spectral response of colored inks becomes a controlling factor. The spectral reflectance of some inorganic inks is shown in Fig. 4. For good contrast, the ink must absorb energy from the light source and not reflect it. A green light source wtih a narrow bandwidth is ideal for copying blue, violet, orange, red, brown and black inks. Zinc ortho silicate phosphor, for instance, has a bandwith of only 530 Angstroms and has a high peak energy output (1.4 watts per 100A band at the peak for the 40T12 lamp). It is used extensively in photocopy fluorescent lamps. The spectral energy distribution curve for the green phosphor is shown in Fig. 5. The chemicals used in the sensitized layer of many papers are also highly sensitive to green light. For some applications the standard fluorescent colors, such as cool white or daylight, are desirable. The chief merit of the fluorescent light source for reflex copying is the fact that it can be designed to radiate with high peak efficiency at practically any wavelength and, having a relatively narrow bandwidth, will effect high contrast for any combination of colored inks which the prospective user would desire to reproduce.

Xerography

In this process the original is projected to a charged surface through a lens system or by contact under exposure to light. The differentially charged surface (plate or drum) is then used to obtain a print on regular white paper. The process will copy translucent originals as well as opaques with printing on both sides. Xerographic plates do not have a peak response in the visible light region but for good contrast for a variety of ink colors a light source which has a narrow bandwith and peaks in the visible range is often desirable. The green zinc ortho silicate lamp is ideal for this application.

Special Light-Copying Lamps

Reflector Lamps

The utilization of light output can often be improved, for some machine types, by the use of lamps with an internal reflector coating. The reflector coating angle depends upon the application. The standard material used, titanium dioxide, has a high reflectance efficiency (90 per cent) in the visible light region but is entirely inadequate for ultraviolet lamps. However, a new material devel-

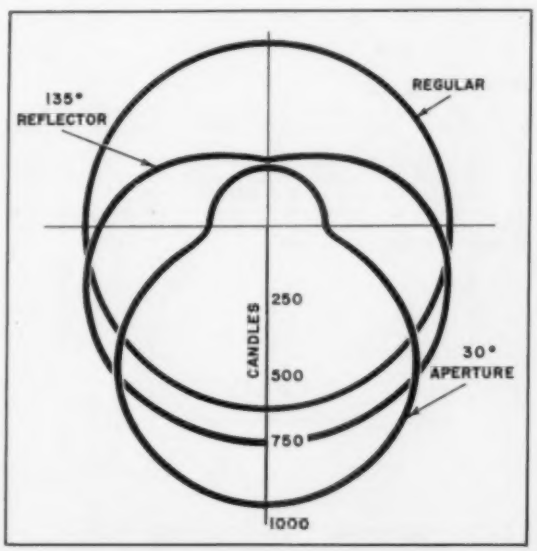

Figure 6. Candlepower distribution for the 30-degree aperture lamp, 135-degree reflector lamp and regular lamp, all lamps operated at 25 watts per foot loading.

oped for light copying lamps has as good reflectance in the violet-ultraviolet range as does the standard coating in the visible range. Candlepower distribution for the 135-degree reflector coated extra-high-output lamp is shown in Fig. 6.

Aperture Lamps

The recently developed aperture lamp,[3] a unique light source, is especially useful where the projection of a high intensity beam of light onto the work area is necessary. The lamp is particularly useful for machines which employ image-projection or image-scanning principles. With the use of standard reflector coating or the newly developed ultraviolet reflector coating, aperture lamps can be designed to give peak output in the entire range from the upper limits of the visible region down to as low as 3600A. The beam candlepower distribution for a 30-degree extra-high-output lamp is shown in Fig. 6.

Conclusion

A great majority of light copying equipment manufacturers, both in America and abroad, are now designing machines around the fluorescent light source. The source has high efficiency, generates little heat and can be designed to match the spectral response of practically any type of paper. The reflector lamp and the aperture lamp principles allow the use of the lamp in many unique applications where a high brightness source of exact dimensions is required for light projection. The development of lamps for higher and higher loadings along with the development of new papers with vastly increased speeds is hastening the day when the fluorescent lamp will become the most widely used light source for light copying.

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DISCUSSION

J. G. WARES:* The lamps referred to in the paper were the very-highly-loaded 1.5-ampere lamps (possibly with even higher loadings) as a source of high brightness generating very little heat. At the moment there is a need for auxiliary equipment to run highly-loaded lamps smaller in size than the four-foot model. Certainly, if such ballast equipment were available, a lot more test work could be done on the use of a highly-loaded lamp for new models of photo-duplicating equipment.

The author lists the following advantages of the fluorescent lamp as a source of energy for photo-duplicating equipment: (a) develops little heat; (b) special cooling can often be dispensed with; (c) it comes up to full efficiency at once.

Experience with the highly-loaded lamps has shown that a *long* stability time is necessary before the lamp reaches maximum efficiency. In measuring these lamps, approximately 80 hours of burning are necessary in the warm-up circuit; then, an additional 15 hours in the measuring circuit are needed before the lamps are stabilized. Will this warm-up period, so necessary on highly-loaded lamps, be a drawback for this new application?

The author mentions high-speed papers and high-efficiency fluorescent lamps as light sources, but no definite values of energies required have been mentioned. What levels of energy are we striving for?

The paper refers to a new ultraviolet reflector coating that will be used in place of titanium dioxide so that higher reflectance efficiencies, especially in the ultraviolet region, can be obtained. Is the author at liberty to furnish more data on this new coating?

C. J. BERNIER:** A photo-duplicating machine using a fluorescent lamp as its light source is ready for immediate use the instant that it is turned on. The long stabilization period (approximately seven hours) is only required when the machine is first placed in operation. Small changes in light output due to lamp stabilization are not reflected in the printing speed.

The level of energy required incident to the paper for photo-duplication service is on the order of .01 joules/centimeter.[2]

In reply to Mr. Wares's final question, I regret that I am not at liberty to reveal, at this time, the nature of the special reflector coating used in the ultraviolet photo-duplicating lamps.

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**Author.

Color of High Pressure Mercury Lamps

By C. W. JEROME

The color of high pressure mercury lamps is affected by the mercury vapor pressure, phosphors are used to supplement the emission, filter coats are used to obtain special effects. Each of these effects is discussed and chromaticity coordinates given for various standard types of lamps.

Much material has been published about the high pressure mercury lamp. Every year three of four mercury papers are presented at the National Technical conference of the IES. However, these have been primarily concerned with operating characteristics and applications. Elenbaas[1] does treat the variation in intensities of the various spectral lines which determines the color of these lamps, but no specific information on their chromaticity coordinates has been found. It is the hope to fill this gap that has prompted the present paper.

The color of the discharge is affected by the mercury vapor pressure, phosphors are used to supplement the emission, and filter coats are used to obtain special effects. In the paper, each of these will be considered in turn.

Effect of Mercury Vapor Pressure

The vapor pressure of mercury within a discharge is determined by its temperature. This, in turn, is determined largely by the power input. Devices with low specific power inputs, such as the fluorescent lamp, operate at a relatively low temperature and, consequently, at a low mercury pressure. High pressure mercury lamps obtain their high pressure by virtue of a high power input in a relatively small arc which results in a high operating temperature. The relationship between vapor pressure of mercury and temperature is shown in Fig. 1. This is taken from Lowry[2] and indicates the operating temperatures from which are derived the useful mercury-vapor pressures for a number of the more important electronic devices.

The mercury emission consists of a number of spectral lines. The relative intensities of these lines

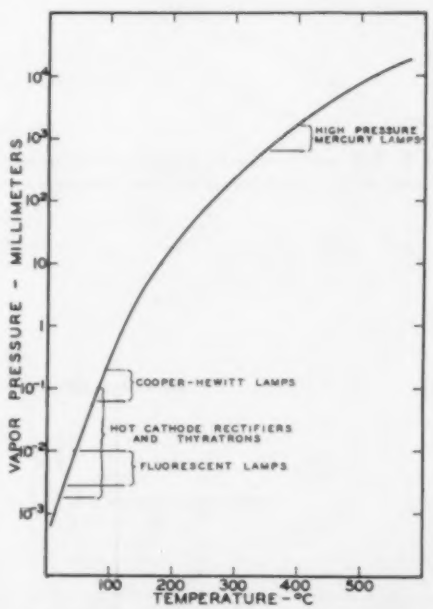

Figure 1. Mercury vapor pressure as a function of temperature. The useful pressure and temperature ranges for various electronic devices are indicated.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. Author: Sylvania Lighting Products, Inc., Salem, Mass.

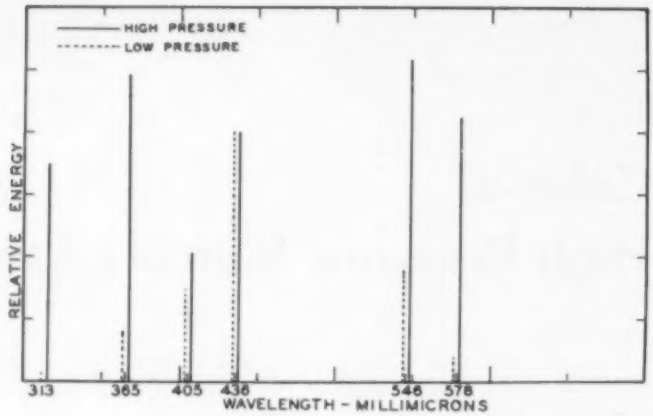

Figure 2. Comparative spectral emissions of high and low pressure mercury arcs.

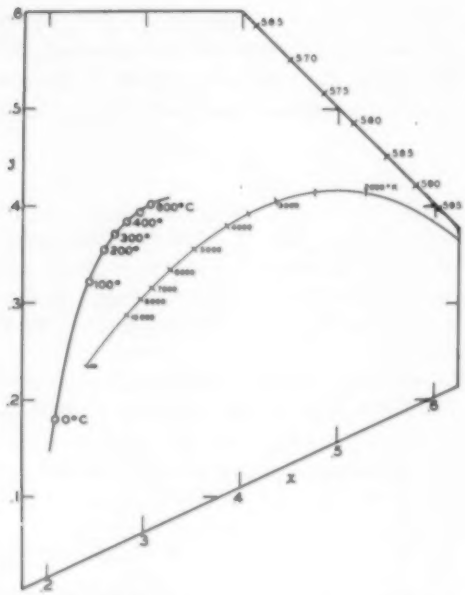

Figure 3. CIE color mixture diagram showing chromaticity locus of mercury arc at various temperatures.

in the visible region of the spectrum determine the color of the arc. Fig. 2 shows the relative intensities of the visible lines of two arcs. One is that of a typical high pressure mercury lamp; the other is that of a low pressure arc, as found in a fluorescent lamp. These have been adjusted so that the blue lines at 436 millimicrons have the same intensity. There are other lines in the mercury spectrum, *e.g.*, at 377,390 and 490 mμ. However, these are so low in intensity as to be insignificant. It will be noted that the major difference in the visible arcs shown in Fig. 2 is in the green and yellow lines at 546 and 578 millimicrons. The high pressure arc is richer in green and yellow energy than the low pressure arc and, consequently, its color is greener and more yellow. The change in color from the low to high pressure arc is continuous and gradual. This is shown in Fig. 3 which is a portion of the CIE color mixture diagram. The locus of chromoticity coordinates of the arc color as its temperature, *i.e.*, vapor pressure, changes is plotted on this. The lower half of this locus is from data on fluorescent lamps, presented in 1953,[3] the lowest point

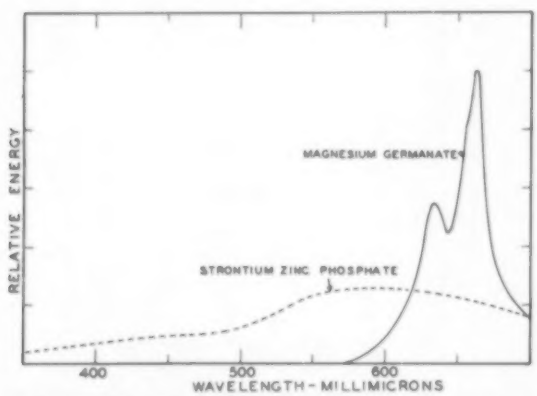

Figure 4. Spectral emission of fluorogermanate and orthophosphate phosphors.

TABLE I—Chromaticity Coordinates of High Pressure Mercury Lamps.

	Arc		Phosphor		Lamp	
Bare Lamp at	x	y	x	y	x	y
0C	0.210	0.180				
100C	.244	.321				
200C	.259	.355				
300C	.270	.370				
400C	.282	.384				
500C	.295	.394				
600C	.307	.403				
Standard Lamps at Normal Operation						
H15GV	.302	.392				
H12GV	.330	.404				
H22KD	.306	.388				
H1LS	.311	.391				
H1LB/W	.311	.394	.434	.410	.350	.400
H1LB/C	.332	.436	.543	.314	.375	.410
H1GL/Y	.415	.568	.624	.373	.443	.542
H1GL/X	.335	.426	.600	.300	.390	.400

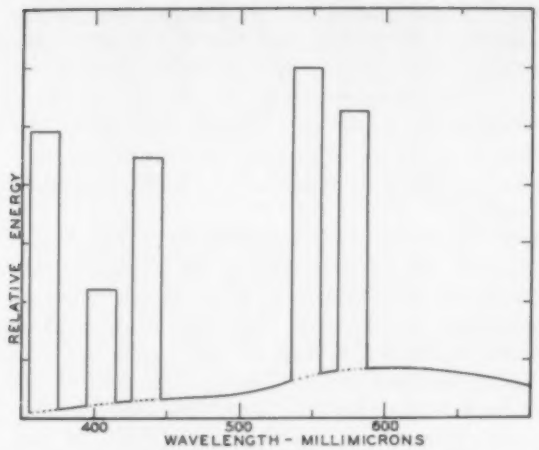

Figure 5. Spectral energy distribution of H1LB/W lamp.

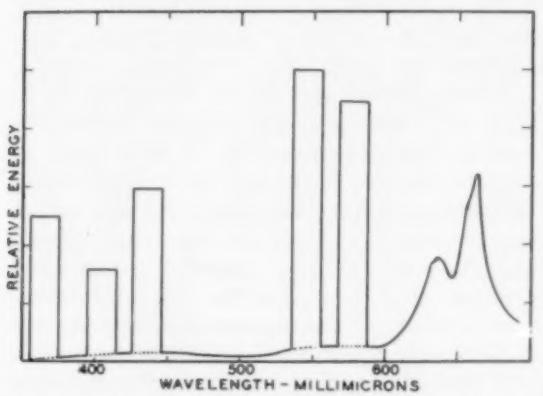

Figure 6. Spectral energy distribution of H1LB/C lamp.

being for a bulb wall temperature of —20C. The upper half of the curve resulted from numerous measurements on several types of clear mercury lamps operated at various arc tube temperatures. There was sufficient overlap in the measurements on the two types of lamps to insure that this locus was indeed a single and continuous function.

Practical mercury lamps are constructed with a limited quantity of mercury so that at their normal operating temperature all the mercury is vaporized in order to stabilize the operating characteristics of the lamps. All the lamps measured at their normal operating conditions have arc tube temperatures slightly above 600C and colors within a very small range at the upper end of the curve shown in Fig. 3. The locus of points continues beyond the range shown. Considerations of the very high pressure lamps, which require high lamp voltages are not, however, within the scope of this paper.

Chromaticity coordinates of the arc at representative temperatures are listed in Table I.

Effect of Phosphors

Since the visible radiation from the mercury arc consists of only a few spectral lines, as shown in Fig. 2, its color rendition may be considered rather unsatisfactory for blue greens and, most especially, for reds and purples. Phosphors deposited on the inside of the outer jacket have been used to correct this deficiency. Thomas et al.[4] have pointed out that these phosphors have the following unique requirements:

(1) They must respond efficiently to a wide

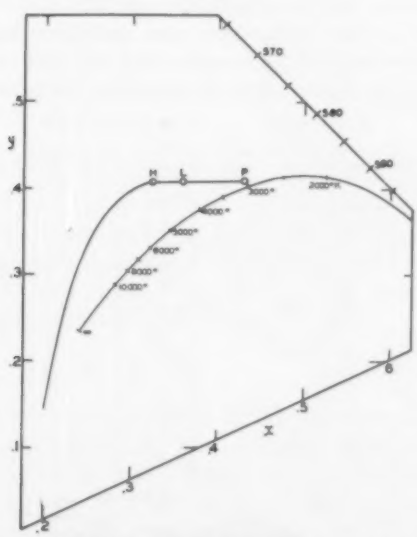

Figure 7. CIE color mixture diagram showing chromaticities of H1LB/W lamp and components. H—arc color, P—phosphor color, L—lamp color.

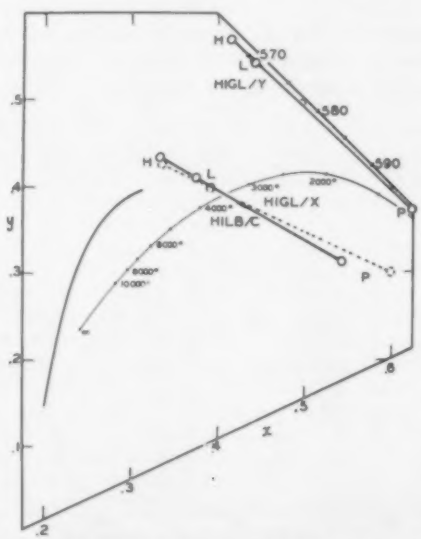

Figure 8. CIE color mixture diagram showing chromaticities of H1LB/C, H1GL/X and H1GL/Y lamps. H—arc color, P—phosphor color, L—lamp color.

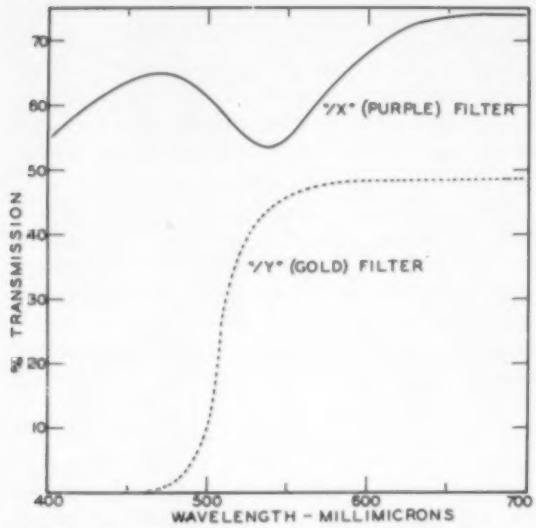

Figure 9. Spectral transmission of "/Y" and "/X" filters.

range of ultraviolet wavelengths, with response to 313 and 365 mμ being especially important.

(2) They must retain high fluorescent efficiency at elevated temperatures.

(3) They must be stable at high temperatures, to the effects of ultraviolet and chemically active gases in the lamp envelope.

(4) They should have a substantial part of their emission in the long wavelength end of the spectrum, if color rendition of reds is to be improved.

(5) They should emit near the middle of the visible spectrum, in addition to the red, if loss of lumen output is to be avoided.

The reason for the first of these requirements is illustrated in Fig. 2. There it will be noted that whereas the 313 and 365 mμ lines are relatively insignificant in the low pressure arc, they are of major proportions in the high pressure arc. At the same time, the 254 mμ line (not shown) decreases from approximately 50 times the 436 mμ intensity in the low pressure arc to only about one-fourth its intensity in the high pressure arc; hence, the importance of the 313 mμ line and the 365 mμ line in the activation of phosphors for the high pressure lamps.

To date only two phosphors have found any extensive use in these lamps— an orthophosphate described by Thomas[4] and the fluorogermanate phosphor. The spectral emissions of these phosphors are shown in Fig. 4. Magnesium arsenate has an emission almost identical with that of the germanate and has been used extensively in Europe. However, it has not found favor in this country because of its toxic qualities.

Just as in the fluorescent lamp, these phosphors contribute to the over-all color of mercury lamps. However, whereas in the fluorescent lamps they constitute the major portion of the lamp emission (approximately 95 per cent), in the high pressure lamps they contribute only about 15 per cent of the total energy emission. Hence their effect on color is correspondingly less in mercury lamps. The fluorogermanate has all its emission in the long wavelength end of the spectrum. Consequently, it contributes considerably to improved rendition of reds in accordance with the fourth criterion above. However, since it is near the end of the visible spectrum, this emission contributes very few lumens, and lamps with this phosphor have lower lumen outputs than the corresponding clear bulb lamps. On the other hand, the orthophosphates have appreciable emission near the middle of the visible spectrum and have higher lumen outputs in accordance with the fifth criterion above. Lamps with this phosphor have lumen

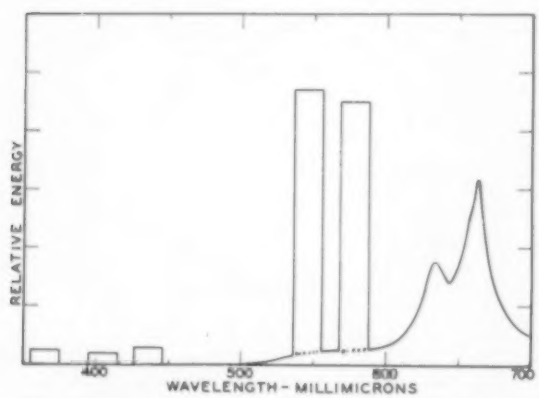

Figure 10. Spectral energy distribution of H1GL/Y lamp.

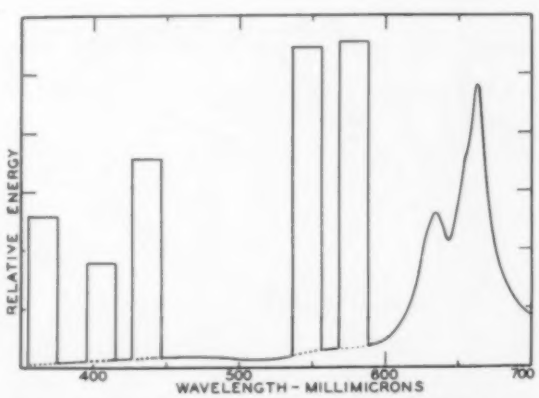

Figure 11. Spectral energy distribution of H1GL/X lamp.

outputs considerably higher than the corresponding clear bulb lamps. Typical spectral energy distribution of lamps with these phosphors are shown in Figs. 5 and 6. It will be noted in these illustrations that we have followed the convention of depicting the spectral lines of the mercury arc as blocks of energy with a definite width—in this case, 20 $m\mu$. This is done to keep the line spectra within reasonable height when drawn on the same basis as the continuum of the phosphor.

The color parameters of these lamps are shown plotted on the CIE diagram in Figs. 7 and 8, and listed in the table. On these, the separate points for the arc, phosphor and combination are shown. For reference, the locus of arc colors shown in Fig. 3 is also shown in these figures.

In the H1LB/W lamp (Fig. 7) it will be noted that the arc color coincides with that for the bare lamp. However, the fluorogermanate is a slightly yellow powder instead of being white. As a consequence, it acts as a yellow filter and the arc in lamps using this phosphor is yellower than in a bare lamp.

Effect of Filters

The high pressure arc is an efficient high intensity source. Being in a relatively small package, it lends itself to use with filters by which special color effects can be obtained. Its line spectrum limits its usefulness in this respect. However, good blue, green or yellow can be obtained in this manner by isolating the desired spectral lines.

As of this time only two filters have found sufficient utility to warrant making them an integral part of the lamp and both of these are used in conjunction with the color improved lamp with fluorogermanate phosphor. These filters are a yellow[4] resulting in the lamp with the color designation "/Y," which is golden in color, and a purple which results in a color designated as "/X." The spectral transmissions of these filters are shown in Fig. 9 and the spectral energy distributions of the H1GL/Y and H1GL/X lamps are shown plotted on the CIE diagram in Fig. 8. The effects of the the filters are as would be expected from their spectral transmissions.

Summary

Factors affecting the color of the high pressure mercury lamps have been discussed briefly. Table I presents pertinent chromaticity coordinates resulting from this study. It is hoped that these data will be of interest and utility to users of these lamps.

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3. Jerome, C. W.: "Effect of Temperatures on Electrical and Color Parameters of 40T12 Fluorescent Lamps," ILLUMINATING ENGINEERING, Vol. XLIX, No. 5, pp. 237-242 (May 1954).
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DISCUSSION

M. C. UNGLERT:* Mr. Jerome indicates that the energies represented by the bars in Figs. 5 and 6 cover a 20 mμ width. This being the case, our data on similar lamps are not quite in agreement with those of the author. We find the energy in the area of 577-579 mμ to be greater than at 546.1 mμ for both the germinate and the orthophosphate coated lamps.

Although the peak values are higher at 546.1 mμ, the width of this line is less than in the 577-579-mμ range, resulting in more energy at the longer wavelength. Could Mr. Jerome supply data of the energy in watts indicated in the important regions of the spectrum.

W. E. THOURET:** High pressure mercury lamps are the basis of the most economical industrial and street lighting installations that can be built today. Therefore, a discussion of their only critical characteristic, their color, and of the available methods of correcting it, is always of great interest.

Mr. Jerome shows the effect of the operating vapor pressure on the chromaticity coordinates of mercury lamps. His results confirm the well-known fact that with increasing pressure the color changes toward a whiter impression, primarily through the increase of continuous radiation which contains a certain amount of red. I would like to ask Mr. Jerome whether he has considered the possibility of improving the color of present mercury lamps by increasing their operating pressure. He states that he does not consider in his paper high pressures that would require higher than usual lamp voltages. However, it seems that the vapor pressure could be raised considerably without changing electrical characteristics by using shorter electrode spacings. Thus, the wattage per unit of arc length could be increased and a slight improvement in luminous efficiency obtained together with a color improvement.

Mr. Jerome's data also show the influence of two other methods of color correcting mercury lamps: the use of phosphors and of filters. When studying the paper I got the impression that a more complete picture of the results achieved with phosphors and filters could be obtained by taking lumen/watt figures into consideration. These show, for example, that the purple filter—which so far seems to be the only means of achieving really satisfactory color rendition—leads to a considerable loss of lumens/watt.

If such reduction in efficiency is to be accepted, the very early method of modifying the color of mercury lamps by adding the light of incandescent filaments appears in a new

*Westinghouse Electric Corp., Bloomfield, N.J.
**Duro-Test Corp., North Bergen, N. J.

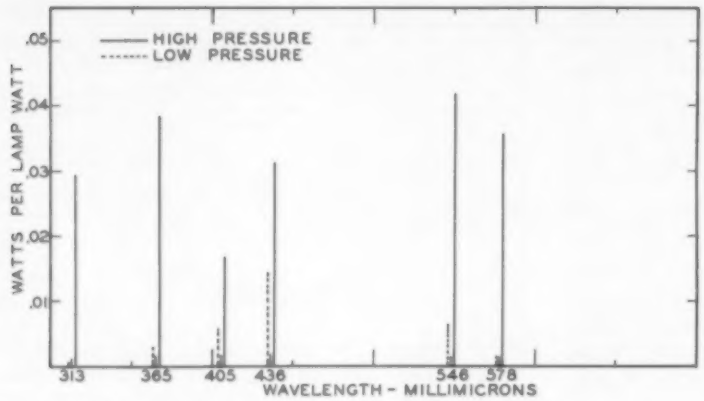


Figure A. Comparative spectral energy distributions of high and low pressure mercury arcs in absolute units.

perspective. In a 1958 IES Conference paper,[1] Mr. H. S. Strauss and I showed that self-ballasted mercury lamps with fluoro-germanate phosphor can be built to achieve at least the same color quality as lamps with a purple filter, with only slightly lower over-all efficiency. It would be of interest to study the chromaticity coordinates of such lamps under variation of wattage ratio between mercury arc tube and ballast filament.

As a last question, I would like to ask Mr. Jerome for some experimental details about the methods used for obtaining spectral energy distributions. For example, what type of monochromator was used, how was it calibrated, and what was the procedure of measuring a relatively weak continuum in the presence of strong line emission? If such experimental details were known it would be easier to correlate Mr. Jerome's results with those of earlier authors who published similar studies.[2, 3]

1. Strauss, H. S. and Thouret, W. E.: "Self-Ballasted Vapor Lamps—New Basic Design Data and New Improved Types," ILLUMINATING ENGINEERING, Vol. LIV, No. 2, page 96 (February 1959).
2. Thorington, Luke: "Temperature Dependence of Emission of Improved Manganese-Activated Magnesium Germanate Phosphor," *Journal of Opt. Soc.*, Vol. XL, No. 9, page 579 (September 1950).
3. Buttolph, L. J.: "Characteristics of Mercury in Lamps," ILLUMINATING ENGINEERING, Vol. XLIX, No. 7, page 321 (July 1954).

C. W. JEROME:* The spectroradiometer used for the determination of the emission curves shown in this paper has been described in an article entitled "Recording Spectroradiometers for Luminescent Materials."[1] In brief, this method uses a modified Beckman monochromator with a constant 5 millimicron band pass. It is calibrated by means of a standard lamp obtained from the Bureau of Standards. Normally, only relative energy values are determined. The absolute values shown in Fig. A, a revised version of Fig. 2, were determined by adjusting the relative values so that $\Sigma E \mu \bar{y} \times 680 =$ lumen output. In this case, $E\mu$ will be in watts. The values for Fig. 2 were divided by lamp watts so that the 400-watt and 40-watt data could be put on the same scale. The actual values for the various lines in the 400-watt high pressure lamp are shown in Table A.

With the 5 millimicron band pass the doublet at 577-579 millimicrons is not resolved but shows up as a single maximum value at 578 millimicrons. With the spread of the doublet, there is an error in this measurement which analysis shows to be 20 per cent. Correcting the value shown in Table A for this doublet leads to a value of 17.80 watts for this line, or slightly above the value for the 546 millimicron line as indicated by Mr. Unglert.

Mr. Thouret's discussion of methods of increasing the weak continuum of these lamps and thereby improving their color rendition is interesting. However, in this study the main interest has been in the lamps as they are now being manufactured. Actually, it is seriously doubted whether much improvement could be obtained by these methods because the spectral lines of mercury are so intense in these lamps that any continuum, whether due to increased mercury vapor pressure or ballasting filaments, would be insignificant and could not be shown on any diagram on which the spectral lines are shown. For example, a continuum exists for the lamps in Fig. 2, however, it is on the order of one per cent of the intensity of the 546 millimicron line, or in Fig. 2, somewhat less than the width of the baseline.

1. Parsons, S. L., Martin, A. E. and Roberto, S. N.: "Recording Spectroradiometers for Luminescent Materials," *Journal of the Electrochemical Society*, Vol. XCVII, No. 2 (February 1950).

TABLE A.

Wavelength (Millimicrons)	Energy (Watts)
313	11.76
365	15.38
405	6.63
436	12.53
546	16.80
578	14.25

*Author.

How Operating Position and Circuit Variations Affect Mercury Lamp Characteristics

By H. D. FRASER W. M. WALDBAUER
M. C. UNGLERT J. A. WALICK

An investigation was made into the effect which variation of operating position and circuit parameters has on the characteristics of a group of H-33/CD-1 400-watt mercury vapor lamps. Various requirements for both "wattage" and "lumen" methods of compensation are discussed. Recommendations are made regarding the establishment of additional lamp standards.

ADVENT OF THE horizontal burning position for mercury vapor lamps has led to the recognition that lamp characteristics are a function of operating position. Both lamp wattage and lumen output decreased as the lamp was rotated from vertical to horizontal. This effect gave rise to the desire to correct or compensate for this change.

Two general methods have been used to provide compensation. "Wattage" compensation has as its basis the increase in wattage delivered to the lamp so that it operates at rated wattage in the horizontal position. It was noted, however, that this did not produce rated lumens in the horizontal position. "Lumen" compensation provides for an increase in wattage to the lamp sufficient to allow it to produce rated lumens in the horizontal position.

Historically, street lighting service incandescent lamps have been designed for lumen output. Variations between lamp types (series, multiple, group replacement series, or regular series) have been adjusted by changing the wattage required to deliver a specific lumen rating. Mercury vapor lamps, however, have been designed for specific wattage values. Technological advances and/or variations in lamp type have kept the wattage constant and let the lumen output vary accordingly. The degree of compensation required to achieve either type of compensation is dependent upon lamp type and circuit used, as well as upon operation position. In the following sections, the effect of varying operating position and circuit parameters on the characteristics of a group of H33-1-CD 400-watt mercury lamps is investigated.

Effect of Operating Position On Lamp Characteristics

In order to determine the changes in operating characteristics of a mercury lamp when burned horizontally *vs.* vertically, a group of H33-1CD 400-watt lamps were tested. They were selected for this test because the 400-watt is by far the most widely used type and the improved oxide-coated electrode is rapidly becoming the most popular.

The lamps were installed in a spherical photometer with provisions for turning the lamp from the vertical to the horizontal position without extinguishing as well as rotating the lamp about its axis. Observations were made using a standard linear reactor ballast with 7½ per cent power factor and providing means for adjusting the impedance to desired values. Voltage, current, wattage, and lumen output were read both vertically and horizontally, by rotating the lamp and taking readings at four points 90 degrees apart at each of the impedance values.

The results of these tests are shown in Figs. 1 and 2. In Fig. 1, the two curves at the top indicate the change in lamp wattage as the impedance is varied. The curves represent the average of all lamps tested whose operating voltages are as indicated in Table I. It can be seen that for the H33 type, the vertical to horizontal wattage difference over the range tested is relatively constant and is approximately two per cent lower in the horizontal position. At the bottom of the graph, the effect on lumens is similarly shown. Again it is evident that the lumens in the horizontal position are lower by a fairly constant amount and are approximately seven per cent lower for the same impedance value. It is, therefore, evident that to obtain rated watts or lumens when lamps are operated horizontally, the circuit will have to supply more than rated watts to a vertical burning lamp. For example, with a circuit such as used for these tests, a ballast operating the lamp in a vertical position at 400

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHORS: Messrs. Fraser and Unglert, Westinghouse Lamp Division, Bloomfield, N. J.; Messrs. Waldbauer and Walick, Westinghouse Lighting Division, Cleveland, Ohio.

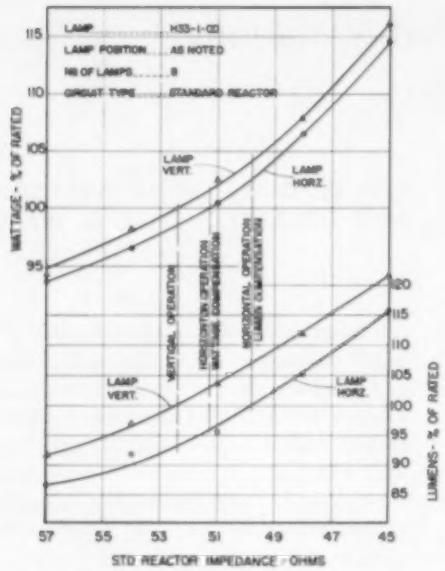


Figure 1. Effect of ballast impedance and lamp position on lamp characteristics.

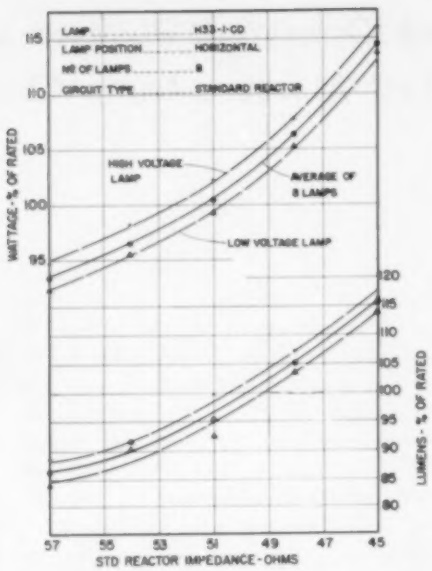


Figure 2. Effect of ballast impedance and arc voltage on lamp characteristics.

watts and giving rated lumens will run the same lamp horizontally at only approximately 392 watts and about 93 per cent of rated lumens. If it is desired to compensate the circuit so that the lamp will run at rated watts horizontally, then of necessity the vertical burning lamp must be operated at 408 watts. This will result in a lumen value of 104 per cent of rated in the vertical position. However, the lumen value in the horizontal position of a lamp operated vertically at 408 watts will only be 96 per cent of rated lumens. Therefore, in order to compensate for rated lumens in the horizontal position, a lamp would have to be operated at approximately 416 watts in the vertical position which, as shown before, would result in 107 per cent of rated lumens in the vertical position and would draw 410 watts when burning horizontally.

The above illustrations, as pointed out, refer only to the standard inductive ballast circuit. Other types of ballasts will give different results and the complexity of this problem becomes self-evident.

Fig. 2 indicates the range of lumen output and lamp wattage for lamps tested in the horizontal position, as a result of varying lamp voltages. This shows the additional range of lumens and wattage which will be encountered with variation in lamp voltage between approximately 127 and 143 volts as measured vertically.

From maximum to minimum, there is a range in watts of about 3 per cent and lumens of about 3½ per cent. This is in addition to the variation resulting from lamp burning position. These curves, of course, are true only for the ballast used in the test but do show that lamp operating voltage is another factor to be considered.

It is desirable to discuss the phenomenon that occurs when the arc operates in the vertical position and then in the horizontal position in order to better explain the reasons for the changes in operation as previously presented. In vertical operation, the arc steadies to a constricted position approximately centering itself in the arc tube, as shown in Fig. 3. The convection currents in the vapor phase outside of the arc stream maintain a balanced heat condition so that there is a virtually equal dissipation of heat to the walls throughout the length. However, when the arc tube is tipped to the horizontal position, a change occurs in the convection currents (see Fig. 4) and the effect is to slightly bow the arc upward, thus moving it nearer to the quartz wall. When this occurs, of course, the conduction of heat away from the arc stream to the quartz wall, which is being cooled by gas in the outer bulb, becomes greater, resulting in

TABLE I—Arc Voltage of Test Lamps.

Lamp Number	Lamp Voltage	
	Vertical	Horizontal
1	128.6	126.7
2	128.8	128.5
3	140.0	134.3
4	126.8	125.9
5	141.0	138.2
6	139.6	137.2
7	143.0	139.8
8	141.6	138.0
Average	136.2	133.6

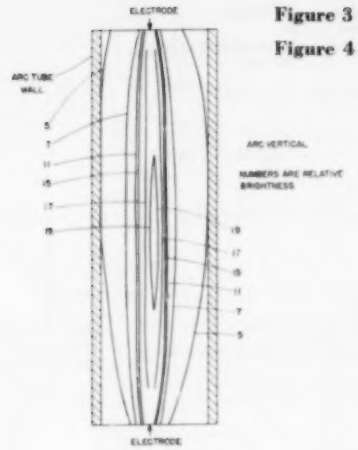
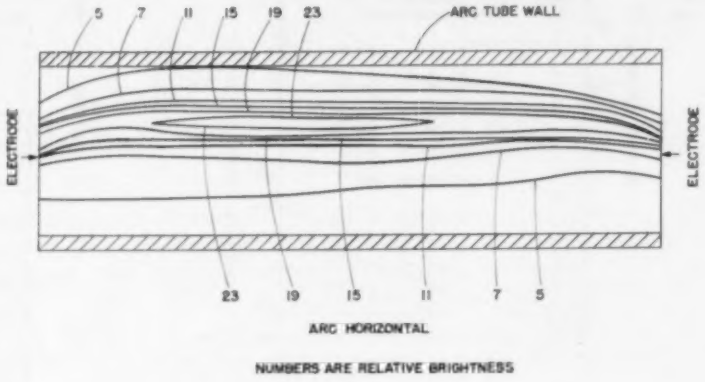


Figure 3 (left). Isobrightness curve of H33-1/CD arc stream (vertical position).

Figure 4 (below). Isobrightness curve of H33-1/CD arc stream (horizontal position).



more of the total energy of the arc being siphoned away in heat losses, leaving less for light production. The greater cooling of the mercury vapor results in lower pressure in the arc and, consequently, a lower arc voltage. This, in turn, drops the wattage.

Effect of Circuit Variations On Lamp Characteristics

The test procedure used to determine the effect of circuit variations upon the lamp characteristics is based on the American Standards Association Specification No. C78.1305-1959 which covers the 400 watt BT-37 (H-1) mercury vapor lamp. Since a similar approved standard is not yet available for the 400-watt BT-37 (H-33), and since the electrical characteristics of the two lamps are nearly alike, it was felt that this approach was justified.

The circuitry used to obtain the lamp operating characteristics is the reference ballast as described in the above mentioned standard; namely, a linear reactor of 53 ohms with a power factor of 7 to 8 per cent as used on a 240-volt 60-cycle per second sinusoidal supply. With this circuit, a reference lamp was selected such that in a vertical base-up position, it was operating within 1½ per cent of the characteristics indicated in C78.1305-1959.

Production ballasts of the reactor, high reactance, and regulated output types (see Fig. 8) were selected such that the aforementioned reference lamp was selected such that, in a vertical base-up zontal position. Thus, the parameters were limited to those of the lamp and supply voltages, and precluded, specifically, those of ballast manufacturing tolerances. Each of the test lamps were then operated on the various circuits. The change from circuit to circuit was made without extinguishing the lamps.

Graphic and tabular reports of the results are shown in Fig. 5, 6 and 7 and Table II respectively. It can be seen from this information that the lumen results were slightly more adversely affected by given changes in parameters than were the wattage values. Particularly notable are the wattage results of the combined variations in line and lamp voltages as opposed to the circuits used. In this light, the least desirable circuit is the reactor, whereas the regulated output ballast indicated a more favorable performance.

In considering the relative lumen ratings as opposed to the circuitry, it should be observed that

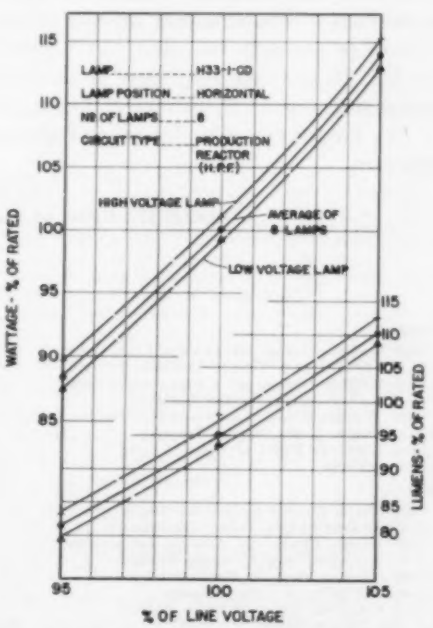


Figure 5. Effect of line voltage on lamp characteristics (reactor circuit).

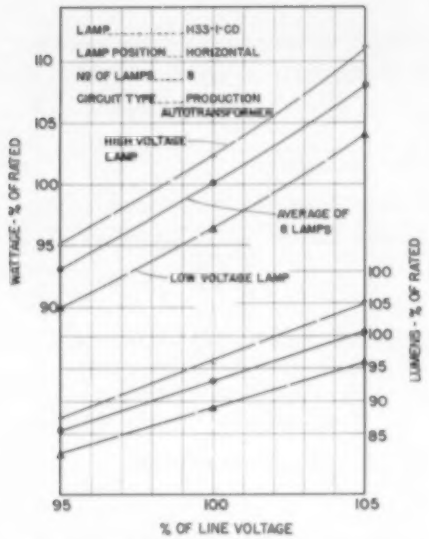


Figure 6. Effect of line voltage on lamp characteristics (auto transformer circuit).

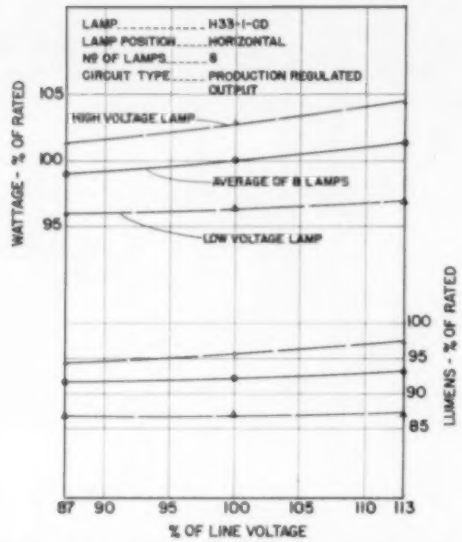


Figure 7. Effect of line voltage on lamp characteristics (regulated output circuit).

the regulated output circuit requires more lumen compensation than the other two. However, the difference in relative values are almost negligible.

Conclusions

One important consideration in the operation of mercury lamps is the reduction of both lamp wattage and lumen output when the operating position is shifted from vertical to horizontal. It is generally agreed that some form of compensation is required for horizontal operation of these lamps. Two methods of compensation suggest themselves: (a) wattage compensation and (b) Lumen compensation. In any case, the degree of compensation required will depend upon several factors including: (a) lamp type and design and (b) circuit parameters.

Some of the advantages and disadvantages of the proposed methods of compensation are as follows:

Lumen Compensation

Advantages—(1) Maximum illumination on the street per luminaire—approximately four per cent gain over wattage compensation for the H33 lamp.

Disadvantages—(1) Effect on lamp temperature, (2) effect on luminaire temperature, (3) increased power costs.

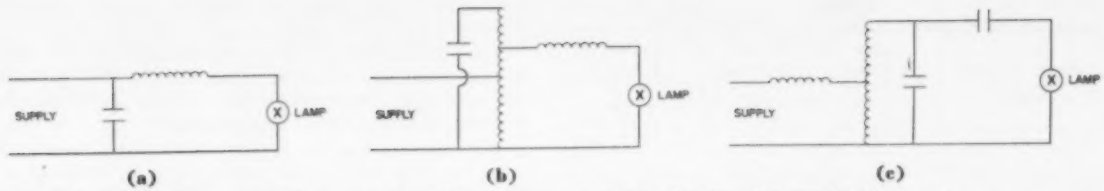
Wattage Compensation

Advantages—(1) Lower lamp temperatures, (2) Lower fixture temperatures, (3) Lower power cost based on a given installation.

Disadvantage—(1) For same initial footcandle value on street, initial cost of system is higher.

TABLE II—Effect of Circuit Parameters on Lamp Characteristics.

Condition	Circuit					
	Reactor		High Reactance		Regulated Output	
Wattage						
Per Cent Wattage Change on Average Lamp Over ± 5 Per Cent Supply Voltage Variation	+14	−12	+ 8	− 7	—	—
Per Cent Wattage Change on Average Lamp Over ± 13 Per Cent Supply Voltage Variation	—	—	—	—	+ 1	− 1
Per Cent Wattage Change at Nominal Line Voltage Due to Lamp Voltage Range	+ 1	− 1	+ 2.75	− 3.75	+ 2	− 3.8
Per Cent Combined Effect of Lamp & Line Voltage Ranges	+15.5	−12.5	+11.0	−10.0	+ 4.5	− 4.0
Lumens						
Per Cent Lumen Change on Average Lamp Over a ± 5 Per Cent Supply Voltage Variation	+15.0	−13.5	+ 7	− 7	—	—
Per Cent Lumen Change on Average Lamp Over a ± 13 Per Cent Supply Voltage Variation	—	—	—	—	+ 0.5	− 0.5
Per Cent Lumen Change at Nominal Line Voltage due to Lamp Voltage Range	+ 1.9	− 1.9	+ 3.4	− 4.4	+ 3.5	− 5.5
Per Cent Combined Effect of Lamp Voltage and Line Voltage Ranges	+17.8	−15.6	+12	−11	+ 5	− 5
Per Cent of Rated Lumen Output at 100 Per Cent of Rated Wattage	95		93		92.5	



(a) (b) (c)

Figure 8. Circuit diagrams: (a) reactor, (b) high reactance auto transformer, (c) regulated output.

The past history of mercury vapor lamp development has keep wattage constant and increased lumen output as improvements have been made. So long as this trend continues, it would appear that wattage compensation is the most logical choice. Now is the time for the industry to confirm that this method of compensation, from an over-all standpoint, best suits their needs. Coincident with this is the need for the establishment of a series of standards similar to ASA C78.1035-1959, as applied to horizontal operating lamps of all wattage classes. It should be noted from Fig. 1 that the standard is dependent on the type of compensation required.

DISCUSSION

E. C. Martt:* Data in the first part of this paper showing wattage and lumen variations with ballast impedance are similar to work being done by several companies in conjunction with ASA Committee C82 on mercury lamp ballasts. We are glad to see it published here, although later it must be compared in ASA, with similar data obtained by others, both as to the results and the methods of measurement. Except for the results obtained with the standard reactor, a considerable amount of data similar to those presented in this paper have been published in a 1956 IES conference paper.[1] Where directly comparable, results agree closely. For example, the authors show that a ballast operating a lamp in a vertical position at 400 watts and giving rated lumens will operate at about 392 watts horizontally. Also, if vertical lumens are to be obtained in horizontal operation, then approximately 416 watts are required. The corresponding values from the 1956 paper are 392 watts and 414 watts, respectively, even though the former data were taken on H1 lamps; however, the electrical behavior of H1 and H33 lamps is very similar.

The authors state that other types of ballasts will give different results, and that the complexity of this problem becomes self-evident. This is certainly true, but I would again like to refer to the 1956 paper[1] where some of these complex factors have been analyzed. Figs. 2 and 3 and Tables I and II in that paper show the behavior of several ballast types over ranges of lamp and line voltage for both vertical and horizontal operation. We find no reference to previous work in this current paper.

In Table I, data are given for the change in lamp voltage from vertical to horizontal operation for the eight lamps used in the test. On the average, the voltage dropped 2.6 volts. This seems low compared to a considerable amount of our own data which show about 4 volts drop. Do the authors believe that 2.6 volts change is typical for their lamps of this type?

In Figs. 3 and 4, showing the isobrightness curve of H33 lamps in vertical and horizontal burning, the brightness distribution seems to be completely in error, in that the arc is shown to have a considerable brightness all the way to the bulb wall. This is contrary to typical published data,[2, 3] and we believe that such distribution curves are misleading for anyone who might attempt to use this information. In vertical operation, for example, arc brightness for the 400-watt lamps is down to 5 per cent of center brightness at a distance of 6 mm from the center in a tube having a radius of 10 mm.

More complete results on the effect of circuit variations on lamp characteristics can be found in the 1956 paper,[1] except for the data given for the high reactance transformer. In Figs. 5 and 6, the range of line voltage from 95 to 105 per cent of normal is less than we believe is found in practice, and this range is rather narrow for comparison with Fig. 7 where a wider range of 87 to 113 per cent is given.

We thoroughly agree with the authors that for horizontal operation, wattage correction is preferable to lumen correction, if any adjustment from normal horizontal values is desired. It should be pointed out, however, that some regulated output ballasts may require a considerable amount of wattage correction[1] (by means of increased lamp current) to restore rated watts. Lamp current should be kept within the tolerance limits to avoid poor lamp performance. If the authors could provide lamp current values for the conditions shown in Figs. 1, 2, 5, 6 and 7, such data would be of considerable aid in evaluating the various circuits for horizontal performance.

1. Noel, E. B. and Martt, E. C.: "Effect of Operating Variables on Mercury Lamp Performance," Illuminating Engineering, Vol. LI, No. 7, pp. 513-531 (July, 1956).
2. Noel, E. B.: "Mercury Lamps Redesigned for Improved Light Output and Performance," Illuminating Engineering, Vol. XLIII, No. 9, p. 1056, Fig. 10 (November, 1948).
3. Elenbaas, W.: *The High Pressure Mercury Vapor Discharge*, North-Holland Publishing Co., p. 12, Fig. 8.

Herbert S. Strauss:* The variations in lumen output and electrical characteristics of mercury lamps, as determined by burning position and type of ballasting equipment used, constitute a well-known problem for the designers, manufacturers and users of mercury lamp lighting. In this connection it is always welcome to have a paper presented which deals with this complex problem.

I would like to ask the authors the following: This paper appears to be a restatement of much of the information presented by Noel and Martt in a paper read at the 1955 IES National Technical Conference.[1] Noel and Martt clearly covered the relationship of vertical to horizontal burning as it affects lamp characteristics. An explanation of the arc

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*Duro-Test Corp., North Bergen, N. J.

TABLE A.

Lamp Position	Lamp Wattage	Lamp Voltage	Lamp Current
0° horizontal	395	133	3.26
15°	396	134	3.23
30°	399	136	3.21
45°	400	136.5	3.19
60°	401	137.5	3.17
90° vertical	402	138	3.16

mechanism when the arc axis is rotated from the vertical to the horizontal was also given, and data for several types of ballasts showing wattage as well as lumen compensation was shown in Table II of that paper. Noel and Martt presented their data based on the H1 lamp. Since the authors believe that electrical characteristics of the H1 and H33 lamps are "nearly alike" can they perhaps emphasize the basic differences between their paper and the publication by Noel and Martt?

I would also like to ask the authors if any data have been taken at other than vertical and horizontal operation? As has been brought out by many discussions in the Mercury Lamp Subcommittee C78-4 of the ASA, many 400-watt luminaires do not burn the lamp in exactly the horizontal position, but rather at 15 degrees to the horizontal. In view of this, the mercury lamp manufacturers have been asked to take data for ASA at 15 degrees and other burning angles to establish a curve. Data we have taken show that lamp wattage, lamp current and lamp voltage vary approximately sinusoidally as the lamp is swung from 0 degrees to 90 degrees (0 degrees = horizontal).

Data for Table A were taken for H33 lamps at 53 ohms impedance with a standard linear reactor at 7½ per cent power factor and a supply voltage of 240 volts. All readings, except the vertical, are averages of four readings 90 degrees apart on the lamp axis.

The question of the type of compensation to be finally employed is also being discussed by the ASA Mercury Lamp Subcommittee with the preference, at the present time, at least, being for wattage compensation. In addition to the disadvantage of lumen compensation, listed by the authors, there is the difficulty of compensations for the different fluorescent phosphor type lamps. Have the authors studied the effects of wattage and lumen compensation for the /C, /W, /X and /Y type lamps?

In conclusion, do the authors have any data on lamp sustaining voltage in the horizontal position as compared to the vertical position?

1. Noel, E. B. and Martt, E. C.: "Effect of Operating Variables on Mercury Lamp Performance," ILLUMINATING ENGINEERING, Vol. LI, No. 7, pp. 513-520 (July, 1956).

R. W. HAGGSTROM:* The laboratory test results reported in this paper compare favorably with my results, reported in "Mercury Ballast as an Integral Part of the Street Lighting Luminaire."[1] Inasmuch as I agree wholeheartedly with the authors' recommendations, I find it difficult to comment other than to make an additional plea for wattage compensation and horizontal lamp standards. It is my contention that no matter what the position, the lamp should always be operated at rated watts.

It should be noted that the recent design refinements in the constant-wattage or regulator type ballasts have produced low operating current crest factors. This will prevent low lumen maintenance when lamps are operated at rated wattage in the horizontal position.

I do disagree on the term, compensation, however. If a ballast is designed to deliver rated watts to a horizontally operating lamp, this is proper operation and the ballast has not been subjected to any compensation.

In today's market, the ballast manufacturers have (and I use the term loosely here) standardized on adjusting indoor ballasts to rated watts vertically and outdoor ballasts (400 watts and higher) delivering rated watts horizontally. This covers the majority of installations. The facts are, that with but one exception, all major ballast manufacturers have been following the above rule.

1. Haggstrom, R. W.: "Mercury Ballast as an Integral Part of the Street Lighting Luminaire," ILLUMINATING ENGINEERING, Vol. LVI, No. 3—Section II, p. 159 (March, 1961).

JOHN LAUGHLIN:* Two methods of compensation for horizontal lamp operation are discussed in this paper, namely, lumen compensation and wattage compensation. Both methods place the burden on the ballast. Is it not reasonable to consider what could be done with the lamp and/or luminaire to compensate for reduced wattage and lumens attendant to horizontal lamp operation?

One well known technique uses a magnet as an arc suppressor on horizontal operating H25 (old AH1) lamps. In this instance there was no choice; it had to be done or the arc tube would have been damaged in a very short time by the heat from the arc. What are the economics of utilizing this old technique so that the ballast will not have to compensate for the deficiencies of horizontal lamp operation? What other possibilities exist for the lamp or luminaire manufacturers to make compensation for horizontal lamp operation? This would be an appropriate time to discuss any possibility that exists.

Fig. 2 of the paper shows the changes in lamp wattage and lumens as determined by arc voltages in a range from 127 to 143 volts. The normal ASA range for a 135-volt nominal lamp is 120 to 150 volts. Why was this official range not used? If a range narrower than 120 to 150 volts encompasses essentially all lamps produced, why are the ASA lamp specifications not brought up to date? After all a plus or minus 11 per cent manufacturing tolerance seems to be extremely broad.

Figs. 5 and 6 of the paper show changes in lamp wattage on a commercial reactor and autotransformer, respectively, for a plus or minus 5 per cent change in primary voltage. However, Fig. 5 shows the change in lamp wattage of a constant wattage circuit with a plus or minus 13 per cent variation in primary voltage. Would it not be a more equitable comparison if all circuits were subjected to the same percentage change in primary voltage? This is particularly important when the data are subsequently used to obtain "per cent combined effect of lamp and line voltage changes" and the "combined effects" of unregulated and constant wattage ballasts are to be compared. Incidentally, how is the "combined effect" obtained? Direct arithmetic addition doesn't quite do it.

Table II shows "per cent wattage change at nominal line voltage due to lamp voltage range" to be less for a regulated output than for a high reactance circuit. This is representative but bears emphasizing. I don't believe this is generally appreciated in the industry.

I heartily endorse the authors' conclusion that wattage compensation for horizontal lamp operation is the logical

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*Sola Electric Co., Elk Grove, Ill.

choice. The main reasons for this choice are lower lamp, luminaire and ballast temperatures. The use of ballasts integral with the luminaire gives rise to the possibility of especially severe lamp, luminaire and ballast heating. With the increases in initial lumen ratings and improved lumen maintenance, wattage compensation is an entirely legitimate choice.

H. A. BREEDING:* This paper presents a very thorough coverage of the subject for the 400-watt lamp. As would be expected, the results confirm that H33 performance is almost identical to that of the almost obsolete thoriated tungsten cathode (H1) design.

The authors indicate, at least in their reactor performance studies, that they have tested each lamp in four rotational positions during horizontal operation. In similar testing we have observed wide variations between the different positions for the same lamp, although the H33 apparently varies less than the old H1 design. Nevertheless, the variation in horizontal lamp wattage, due to rotational position, approaches that for which the authors propose to compensate. This means that if the ballast design is changed, the "horizontal operating position variation" will be around the higher wattage point.

Van Dusen's paper on street lighting glassware breakage[1] points out the critical effects of wattage on glassware breakage. From this, it is already evident that any change in ballast output wattage must necessarily be closely correlated with luminaire design. This too, perhaps, is a subject for ASA work toward wattage standardization.

There are, of course, thermal problems other than glassware which require careful correlation and indicate the positive need for wattage standardization rather than lumen standardization, especially when we are designing for minimum luminaire cost. Therefore, I, too, vote for wattage standardization.

The ballast tests reported in Figs. 5, 6 and 7 of the paper are on the rated wattage basis, indicating that others, as well as ourselves, now work on that basis. The lamp designers, too, will probably prefer the rated wattage approach, since that was the basis for the design.

From the owner's standpoint, the rated wattage approach should be reasonable, since mean lumens are almost identical at rated watts for horizontal and vertical operation with H33 lamps. (With the old cathode design, mean lumens were much higher for horizontal operation at rated watts.) Therefore, my vote is for rated wattage operation as the all-around best solution.

One question arises about Fig. 6. The lamp performance shown indicates that the ballast design has approximately 300 OCV, assuming the circuit shown in Fig. 8b applies. At 240 OCV, the autotransformer circuit would give lamp performance almost identical to that of the reactor, Fig. 5. My question is, do the authors believe that 300 OCV is necessary for the H33 lamp?

1. Van Dusen, H. A., Jr.: "Research on Street Lighting Glassware Breakage," ILLUMINATING ENGINEERING, Vol. LVI, No. 3—Section II, p. 150 (March, 1961).

M. C. UNGLERT:** We must apologize to Messrs. Noel and Martt for not referencing their fine paper on a similar subject presented in 1955. It was felt, however, that a review and re-evaluation of the subject was timely to present the results obtained with the new improved electrode (which is fast becoming standard) in which many people are now interested; to present data obtained with a standard impedance; and, to present the results using the latest in ballast development.

Referring to Mr. Martt's question regarding volt drop between vertical and horzontal operation, a drop of 2.5 to 3.0 volts is believed normal for our lamps. In reference to his comments on the arc brightness dingrams, the results are as we measured them. The purpose of the diagrams is to show the bowing effect of the arc in the horizontal position. In order to draw a diagram which would illustrate this point clearly, it was necessary to limit the number of isobrightness lines presented. The results of our data and those previously presented by Noel in 1948 are quite similar for this type of measurement. For example, Noel's curve shows that the brightness 5 mm from the center of the arc is 16 per cent of the highest measured brightness. Similarly, using our highest brightness point, the brightness at 5 mm from arc center would be 20 per cent.

The data presented by Mr. Strauss for interim positions between horizontal and vertical is certainly of interest. Such data are necessary if all possible cases of burning position are to be covered.

The question of lumen compensation for phosphor coated lamps becomes quite involved, since it depends not only upon the arc characteristics, but also upon the temperature dependence of the phosphor used. This varies with the type of phosphor and also with phosphors made by different manufacturers. This would indeed be an interesting subject for a future paper.

In answer to the question asked by Mr. Strauss, we do not have data to present concerning sustaining voltage horizontal vs vertical.

Mr. Haggstrom's comments on the term "compensation" are well taken. However, this term is generally accepted and has developed because it has always been considered that vertical operation of mercury lamps is standard for the purpose of making measurements.

Mr. Laughlin questions whether compensation could not be effected in the lamp or luminaire. These two approaches have been analyzed many times. It is our opinion that these methods would not be economically sound.

The volt range 127-143 encompasses about 90 per cent of all lamps manufactured at the present time. To compress the range of 120-150 volts, now standard, would result in an unnecessary increase in lamp cost.

The values chosen for open circuit voltage on the various ballasts tested are those recommended by the manufacturer. We felt that it would not be legitimate to draw conclusions from data obtained outside the limits for which these devices were designed.

Since the curves presented are not parallel lines, arithmetic combinations of values selected from the curves cannot be used. The values must therefore be determined from the curves.

Mr. Laughlin's comments concerning the advantages of the regulated output ballast are indeed apt.

Regarding Mr. Breeding's discussion, the authors did not mean to imply that 300 OCV is necessary for the H33 lamp; rather, we chose to test an available standard commercial ballast.

A minimum open circuit voltage of 225 volts rms will start H33 lamps reliably at temperatures down to −20F. Any higher values of voltage will, of course, afford greater protection against drop out resulting from voltage dips.

Finally, we are glad to see the unanimity among the discussers concerning the proposition that wattage compensation be recommended as standard.

*General Electric Co., Outdoor Lighting Department, Hendersonville, N. C.
**Co-author.

40-Watt Fluorescent Lamp with Higher Light Output

By DONALD D. HINMAN
ROBERT S. FOX

Of the 40 watts input to this size of fluorescent lamp, about one-third is dissipated in the filling gas and in electrode losses. None of this contributes directly to the production of light. A reduction in the pressure of the filling gas, and the addition of large area anodes, reduces these losses by approximately two watts with a resultant increase in lumens per watt.

A practical combination of these design changes results in increases of five per cent or more in lumens and lumens per watt. This is independent of, and in addition to, any gains achieved by improved phosphors.

During the twenty years in which the 40-watt fluorescent lamp has been in use, most of the increases in light output have resulted from better phosphors and improvements in processing technology. Although much thought and effort has been devoted to better lamp designs, the introductions of many promising improvements has been limited by the necessity to provide proper performance in existing lighting installations. The extensive application of the 40-watt lamp stimulates a desire in the lamp manufacturer to incorporate into this lamp improvements based on new knowledge, new developments and improved technology. However, a serious handicap is imposed by the requirements that the lamp must start and operate satisfactorily on presently installed ballasts, some of which were designed as long as twenty years ago. The consolidation of the switch-start and rapid-start types into a single universal lamp further increases the problem by requiring satisfactory operation on two different ballast circuits. Even though these limitations are present, several new design features have been successfully incorporated into the 40-watt lamp with a resultant substantial increase in light output and lumens per watt.

Lamp Design Variables

Once the physical dimensions and ballast become fixed for a lamp type, the only design variables, other than phosphor, available for further improvements are the electrodes, filling gas pressure and filling gas composition. Of the 40 watts input to a lamp of the 48T12 size, about one-third is dissipated in the filling gas and at the electrodes. None of this contributes directly to the production of light, and the magnitude of these losses offers potential opportunities for substantial increases in lamp lumens per watt.

Filling Gas Pressure

The decrease in lamp watts with reduced filling gas pressure (Fig. 1) is well known. Shorter lamp life[1] and a higher rate of lumen depreciation at lower pressures have dictated the use of pressures higher than the optimum from the standpoint of efficiency of power conversion. The history of fluorescent lamp development shows a steady decline in filling gas pressures, paralleling improvements in cathodes, phosphors and lamp processing technology. Whereas a filling pressure of four or five millimeters was essential for the earliest lamps, today pressures of two to three millimeters, or even lower, result in a better over-all lamp design.

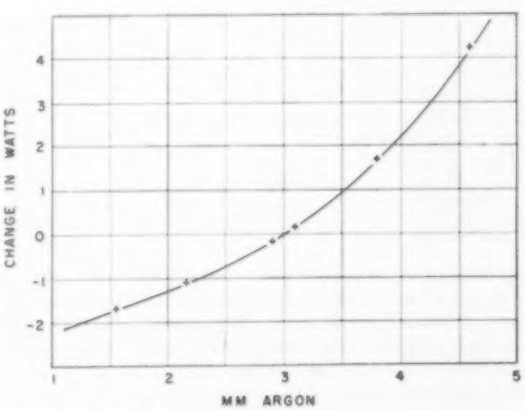

Figure 1. Effect of filling gas pressure on watts of a 48T12 lamp at 0.43 amperes.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHORS: General Electric Co., Cleveland, Ohio. Accepted by the Papers Committee as a Transaction of the IES.

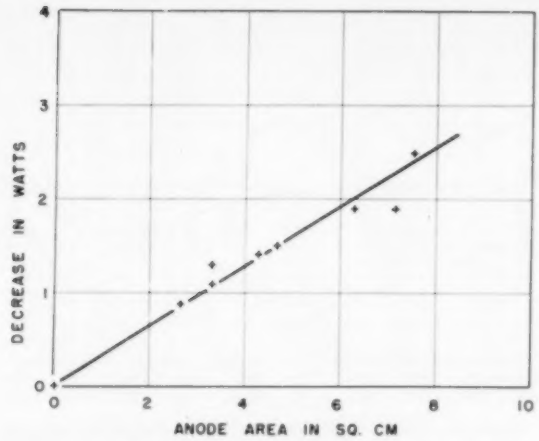

Figure 2. Effect of total anode surface area on watts of a 48T12 lamp at 0.43 amperes.

A reduced filling pressure, then, provides one means of decreasing non-light-producing power in the lamp.

Anodes

The electrodes were also noted as a large consumer of input watts. The lamp electrodes are both cathodes and anodes, performing the two functions alternately as the lamp current reverses in direction. Power is consumed at the electrodes both as an anode and as a cathode. A known but not fully exploited characteristic of anodes is the decreasing losses with larger surface area. The decrease in lamp watts for anodes of various sizes is shown in Fig. 2. The computed area includes both surfaces of the anodes at each lamp end, but not the area of the normal mount structure.

Thus, there are two ways by which the lamp input watts can be reduced: lower pressure and larger anodes. Because of the effects upon other lamp characteristics, it is not possible at this time to take full advantage of all the savings which might be indicated. However, reasonable compromises result in a decrease in input of about two watts without any loss of lumens. This can be achieved, for example, by using a filling pressure of 2.5 mm and an anode area of five square centimeters. In fact, light output is increased slightly because lamp current increases and because lower pressures result in a small lumen increase at the same current.

Filling Gas Composition

Although lamp lumens per watt can be increased by such means, the cost of light is more dependent upon the initial cost of a lighting installation than upon expenditure for electrical energy and, consequently, the lamp lumens per watt. The quantity of light produced by each lamp is of major importance; cost of light in dollars per million lumen hours varies inversely as lumen output.[2,3] The lamp which has been considered here with its lower input watts would have still more value if the input watts were increased to the original value, with a corresponding increase in lumens. Another design variable, filling gas composition, does permit an increase in lamp watts at nearly constant lumens per watt.

The combination of argon gas with mercury vapor is used in most types and sizes of fluorescent lamps. Other gases or gas mixtures are used to advantage in a few lamp sizes because their characteristics are suited to a particular set of conditions. The modified "40-watt" 48T12 lamp with reduced wattage represents a special situation. Here, it is desirable to restore the input watts of a lamp of fixed dimensions back to a previous level for operation on existing ballasts. The addition of neon to the filling gas provides the characteristic of increasing lamp input watts and light output. Lamps with various additions of neon to the filling gas were measured to determine their characteristics (Figs. 3-5). At constant current, the increase in lamp lumens is proportional to the per cent neon in the fill gas. Lumens per watt are nearly constant in the range of zero to 50 per cent neon. The precision of these data is not sufficient to determine the shape of the curve, although there is some indication of a maximum near 30 per cent neon. With higher proportions of neon the lumens per watt tend to decrease toward the value previously reported for 100 per cent neon.[4]

Lumen Maintenance

While neon filling gas provides characteristics which are useful in this particular lamp design

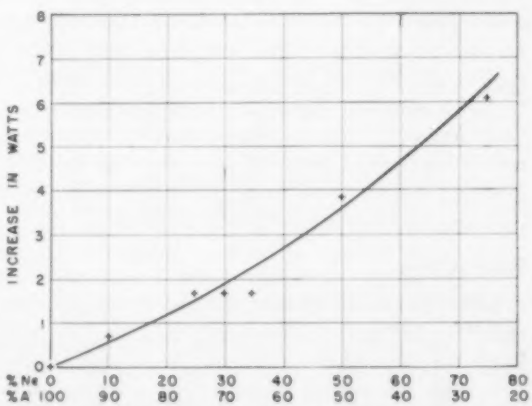

Figure 3. Effect on neon-argon filling gas on watts of a 48T12 lamp at 0.43 amperes.

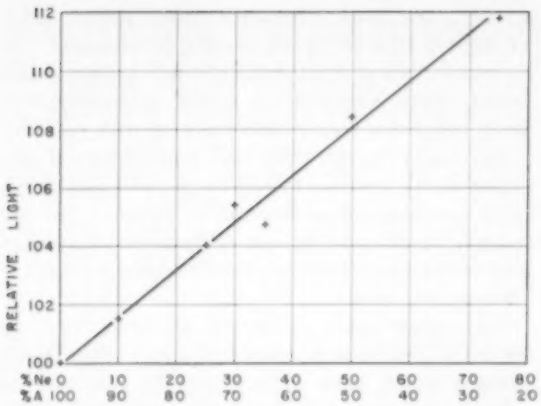

Figure 4. Effect of neon-argon filling gas on the relative light output of a 48T12 lamp at 0.43 amperes.

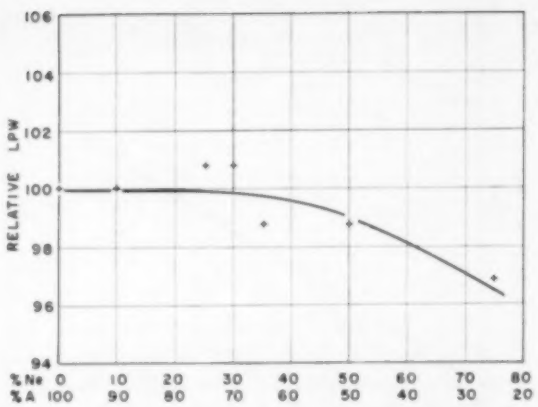

Figure 5. Effect of neon-argon filling gas on the relative lumens per watt of a 48T12 lamp at 0.43 amperes.

problem, all of its characteristics must be given careful consideration. The lower density of neon-argon mixtures generally results in a faster lumen depreciation during the life of a fluorescent lamp than with argon at the same pressure. However, because of the low depreciation rate of today's phosphors, the lumen maintenance at 3000 hours will be only one to two per cent lower for a lamp with 30 per cent neon filling gas as compared to an all-argon lamp. The actual light output will, of course, be higher for the lamp with neon throughout its life.

Lamp Life

Neon gas has a tendency to reduce cathode life. Also, the use of large area anodes requires a change in the cathodes to compensate for the loss of anode heating during the anode half cycle, especially for switch-start operation where the cathodes are heated only by the discharge. The position and shape of the anodes are important; a close spacing between anode and cathode is undesirable, since this tends to increase the cathode fall because of a greater ion loss from the cathode region. Placing the anodes in front of the cathodes is not a solution, since this both obscures ultraviolet radiation and decreases the arc length with a resultant loss of light. A new electrode has been designed which minimizes these difficulties and provides satisfactory lamp life (Fig. 6).

Lumen Ratio

Although published lamp ratings are based upon reference ballast[5] measurements, it is important to know the effect of lamp design change upon operation with commercial ballasts. The usual measure of a commercial ballast performance is the lumen ratio. This is the ratio of lamp light output on a commercial ballast at rated line volts to the light output on a reference ballast. A careful analysis of a number of lamp design variations has shown that the lumen ratio of typical commercial two-lamp rapid-start ballasts is very sensitive to lamp filling pressure. This is a result of the mutual effects of non-linear impedance characteristics of the ballasts and of the short deionization time of lamps with low filling gas pressure.

Two different commercial 40-watt, two lamp series rapid-start ballasts show a decline in lumen ratio with argon filling gas pressure as shown in Fig. 7. In addition, one of the commercial ballasts has a greater loss in lumen ratio for neon-argon

Figure 6. A new electrode design with anodes for use in 40-watt lamps with neon-argon filling gas.

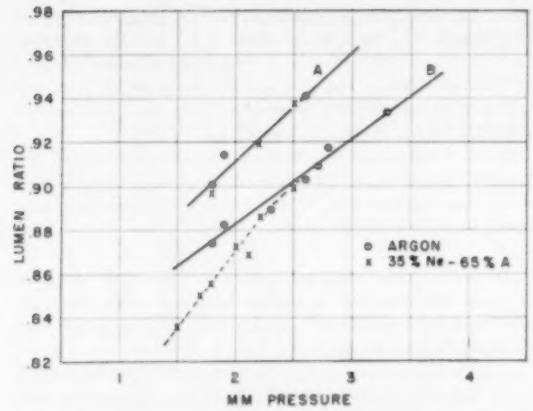

Figure 7. Effect of lamp filling gas pressure on the lumen ratio of two typical commercial 40-watt rapid-start ballasts.

mixtures of less than 2.5mm pressure. For higher pressures the difference between the argon and neon-argon mixtures is negligible. Thus, a neon-argon lamp of approximately 2.5mm pressure has the same lumen ratio as an argon lamp of the same pressure.

Conclusions

A practical combination of these several design parameters—lower filling pressure, larger anodes and addition of a small percentage of neon—results in increases of five per cent or more in lumens and lumens per watt, without changing the lamp input watts. These increases are independent of, and add to, any gains achieved by improved phosphors.

Acknowledgments

The work reported in this paper resulted from contributions of numerous individuals. Special thanks are due K. Schmidt and W. J. Karash.

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DISCUSSION

E. F. KELLEY:* The authors have explored the factors that affect the parameters of fluorescent lamps and have shown not only the effect of each, but also the magnitude of each. The part played by anode size is most interesting and deserves further study.

The operation of this lamp on the older type ballasts is not quite clear to me. There are many preheat ballasts in service and it seems important that lamp operation on these ballasts be completely satisfactory.

The choice of designation of lamp type used in the paper is not the best because 48T12 is usually used to designate slimline lamps.

Does the introduction of this lamp mean that it is to have a different catalogue number and perhaps a premium price? If so, it might be preferable that it be considered an improved version of the F40 preheat-rapid-start lamp, thus avoiding the addition of another lamp to be catalogued and stocked, which would nullify the advantages gained by combining the F40T12 preheat and F40T12 rapid-start lamps.

A. E. FEINBERG:* Messrs. Hinman and Fox have indicated a balanced combination of factors resulting in a more efficient lamp. It is extremely gratifying that they have compared performance with commercial ballasts so that the resulting lamp can be used with existing ballasts.

It is of great interest that the advances shown in this paper overcome some of the difficulties which appear to be present in neon-argon lamps. According to others, the presence of neon with argon has a tendency to create distortion of the lamp current waveshape. This distortion either has not been observed by the authors or has apparently been corrected by modification of the anodes. If the latter is correct, it would appear that the anode voltage drop is a very important factor in the ease with which commercial ballasts can be made to produce good light output with good waveshapes.

There has been considerable trouble in correcting waveshapes of certain types of ballast designs. The introduction of these anodes in other lamps could result in savings in watts and improved ballast characteristics. The improvement in ballast characteristics that would be obtained with modified lamps could result automatically in higher light output from these lamps even though the wattage of the lamps would drop. The increase in efficiency and the total increase in light output would be greater than is indicated with a reference ballast. It would mean an automatic increase in the per cent light output of the commercial ballast as compared to the reference ballast.

C. J. BERNIER:** The authors have presented a clear outline of what can be done to the 40-watt lamp to increase its light output to some extent. The method used is straightforward; *i.e.*, reduce rare gas fill pressure, reduce anode voltage drop, bring lamp wattage back up to rated value by adding the proper concentration of neon to the gas fill at reduced pressure. The question then arises as to whether these design modifications will allow the lamp to give more light output without impairing its performance. The performance of the lamp will be judged against that of the lamp it must replace; namely, the standard 40-watt lamp.

Our experiments indicate that, at the low loading of 10 watts per foot, the addition of neon to argon fill will, in any concentration, reduce the positive column efficiency. However, the over-all efficiency of a short lamp, such as the four-foot source in question, seems to remain constant with

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increased concentration of neon, up to a point. We feel that this is because the ratio of positive column watts to end watts is increased. We would not expect the gain in light output to be as significant in a longer light source, such as the eight-foot lamp. Have the authors found this to be so?

Reduced rare gas pressure will generally result in poorer lumen maintenance. If new means have been developed to improve maintenance at reduced pressure, would not these techniques, if applied to the standard lamp, place this premium lamp in a poorer light?

It has been our experience that large area anodes, placed in the cathode glow region, have undesirable effects on lamp life. They rob the cathode of sorely needed positive ions during the cathode half-cycle of operation and they cause sputtered material to deposit on the cathode during starting. Would the authors care to comment on how the new electrode structure overcomes these difficulties?

The figures of lumen maintenance quoted in the text are given at 3000 hours. Maintenance figures are usually quoted at 60 per cent of lamp life. What is the actual life of this lamp when burned on preheat and rapid-start circuits?

Although a change in cathodes has been made to compensate for the loss of anode heating, the rate of evaporation of cathode material will, at the same temperature, be increased when operating in an atmosphere of reduced pressure and lower-density neon. End discoloration should be materially greater on this source. Do the authors have any relative figures of merit for discoloration?

LUKE THORINGTON:* The authors are to be commended for achieving the apparently rather delicate balance required between the various lamp operating parameters in order to realize a 5 per cent gain in efficacy for the 40-watt fluorescent lamp. One gets the feeling from their paper that, barring a major breakthrough, the last few lumens to be extracted from this lamp are going to be rather costly and difficult to come by.

As is so often true, the gain in relative efficacy is not entirely without an attendant sacrifice—in this case, apparently maintenance and life suffer. Would the authors state what the life of the new lamp is and what its lumen maintenance is at 70 per cent and 100 per cent of life? Normally one might expect more complete life and maintenance data for a new or improved light source. This is true also of efficacy: what is the actual lumen/watt rating for the improved lamp; for instance, for the cool white color? With changes in electrode structure and gas composition and pressure some difference might be expected between the improved lamp and conventional lamps with respect to end discoloration. Have the authors made any observations relating to this?

It is stated that faster lumen depreciation accompanies the use of lower fill gas pressures and lower-density neon-argon mixtures. Is the basic reason for this depreciation understood? The implication seems to be that the phosphor itself is responsible. Finally, I would like to know whether the authors consider changes in bulb geometry to have any potential for the 40-watt fluorescent lamp or is this limited solely to the highly-loaded lamps?

The fact that special attention was directed toward the practical operation of the improved lamp on various existing commercial ballasts was, in my opinion, an especially commendable aspect of the paper.

D. D. HINMAN AND ROBERT S. FOX:* The 48T12 designation was not intended to suggest slimline lamps, but only to indicate that many of the design variations reported were not operating at 40 watts.

A lamp incorporating the improvements reported in the paper has been introduced at a premium price. It is considered an improved version of the standard lamp and has a modified catalog number to distinguish it. The published rating of this lamp in the cool white color is 3100 lumens and 76 lumens per watt. This rating is based upon phosphor improvements as well as upon the design changes discussed in the paper.

The large area anodes do decrease the positive ion heating of the cathode. A new cathode having lower-mass-per-unit length decreases the energy and time required during lamp starting to heat the cathode to a satisfactory emitting temperature, and decreases the power needed during operation to maintain the cathode at this temperature. Variations in ballasts, starters and service conditions result in a wide range in life of standard lamps, so that a single valued rating is no more than some kind of average for these various conditions. A change in lamp design may result in a shorter life for one particular service and longer life for another. When this new lamp is used on rapid-start ballasts and on switch-start ballasts with FS-400 starters, an average life of 7500 hours or more will be maintained.

The variation of lumen maintenance with filling gas density is associated with the penetration of mercury ions into the phosphor. However, the retention of mercury in the phosphor or the resultant damage varies with different phosphors and phosphor treatments.

End discoloration is variable among lamps of a single design. This lamp-to-lamp variation is greater than the average difference between the new and old designs. The same measures that reduce end discoloration in standard lamps will also be effective in this new lamp.

Changes in bulb geometry are interesting possibilities but are outside the scope of this paper.

Our experience indicates that it is not possible to generalize about the effects of lamp design changes upon performance with all ballasts.

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*Authors.

Design and Characteristics of

APERTURE FLUORESCENT LAMPS

By C. L. TOOMEY

Control of light distribution of a fluorescent light source is usually a direct function of luminaire design. Good luminaire design can be more easily achieved when the light source is very small and extremely bright. This has been realized with incandescent lamps which approximate the theoretical ideal point source of high brightness, thereby requiring little or no compromise in the optical design of the luminaire. Precise optical control has not been attained with fluorescent lamps because of their relatively large area and low brightness. Efforts to reduce the apparent area and to increase the brightness have resulted in the lamp discussed here.

Design Factors

The obvious approach to the design of a fluorescent light source of small area and high brightness would be to decrease lamp diameter and increase phosphor loading, *i.e.*, watts/inch^2. However, this design would have serious disadvantages such as poor lumen maintenance, low total lumen output, low luminous efficacy, problems with mercury temperature control, excessive end discoloration and a need for special ballasting. A better approach to the same problem would be to modify an existing fluorescent source in such a manner as to overcome these disadvantages. We have observed that the phosphor brightness on the interior of a fluorescent lamp is much greater than the brightness observed on the exterior. This leads to the conception that if a small window or aperture were to be cut in the phosphor coating the high internal brightness would be revealed and could be utilized in luminaires of proper design. Since interior brightness is a function of the interflections in the tube, the aperture must be made as small as practically possible, so that the most efficient use of these interflections, as described in a companion paper,[1] may be made. It is desired that the luminous flux be reflected back into the interior of the lamp to increase the brightness of the aperture. This may be accomplished by placing a high reflectance material between the phosphor and the glass.

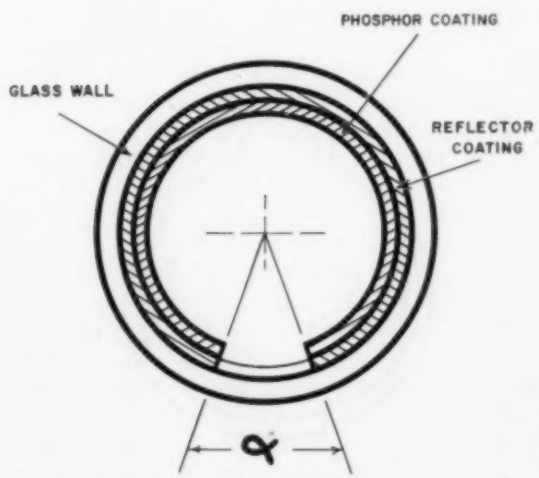


Figure 1. Cross section of aperture lamp showing geometry of construction where aperture width is a function of angle α.

A practical lamp embodying these features has been developed and is shown in cross-section in Fig. 1. The design of this lamp, called the aperture fluorescent lamp, is based on the circular cross-section extra-high-output lamp which is a light source of high brightness and good luminous efficacy. A 30-degree aperture cut into the phosphor and reflector coatings of this lamp along its entire length will show an aperture brightness of approximately 24,000 footlamberts; when phosphor alone is used, the aperture brightness will show a decrease to approximately 12,000 footlamberts. Titanium dioxide is used as the reflector material because it has good reflectivity in the visible light spectrum and because of adaptability to mass production techniques. Fig. 2 is a curve of aperture brightness versus reflector density. This curve shows that an

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHOR: Sylvania Lighting Products, Danvers, Mass. Accepted by the Papers Committee as a Transaction of the IES.

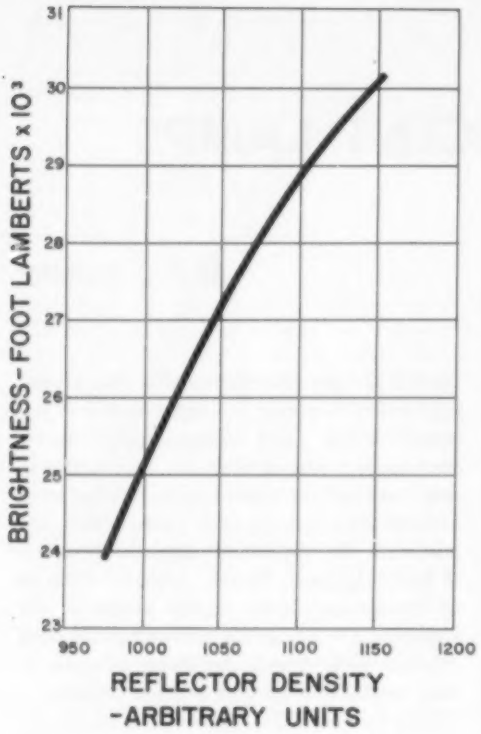
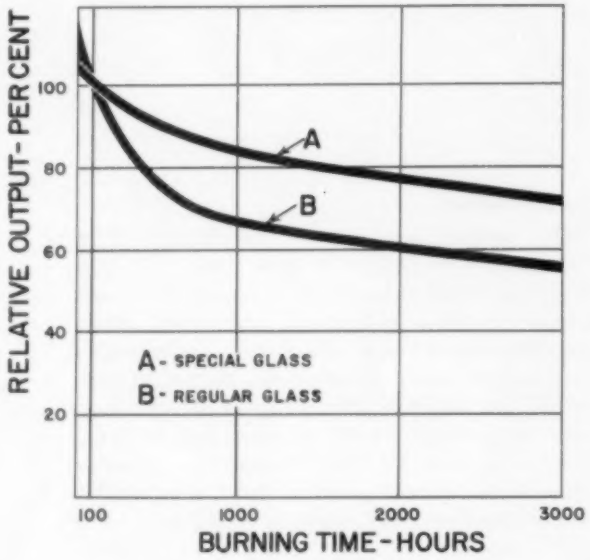


Figure 2 (left). Brightness *vs* titanium dioxide reflector density for the 30-degree aperture lamp.

Figure 3 (below). Aperture lamp luminous maintenance *vs* life for regular glass and special glass.



increase in density or opacity of the reflector material results in an increase in aperture brightness. Table I shows the relative efficacy of various compatible reflector materials used with a 30-degree aperture lamp; titanium dioxide was the material ultimately chosen.

The discoloration of ordinary lime glass under the action of the highly active mercury arc is very severe. By virtue of the inherent design of the aperture lamp, the glass does not have the protection of a phosphor layer and it would, therefore, be correct to assume that poor maintenance would result. However, with the use of special glass the maintenance is no different from that of the regular extra-high-output lamp. Fig. 3 shows the comparison of the maintenance of aperture lamps with and without special glass.

Performance Characteristics

Consideration of the foregoing design factors resulted in an extra-high-output lamp having a 30-degree aperture and titanium dioxide reflector material. In some cases it may be desirable to increase the aperture angle. The larger aperture makes luminaire design less critical, but some sacrifice in distribution control will result.

The electrical characteristics of this lamp are the same as those of the 1.5-ampere extra-high-output fluorescent lamp. Therefore, it will operate on commercially available ballasts.

TABLE I—Relative Efficacy of Various Reflector Materials Used with 30-Degree Aperture Lamp.

Reflector Material	Aperture Brightness (Footlamberts)
Titanium Dioxide	25,000
Zirconium Dioxide	24,000
Phosphor	22,000
Magnesium Oxide	17,000

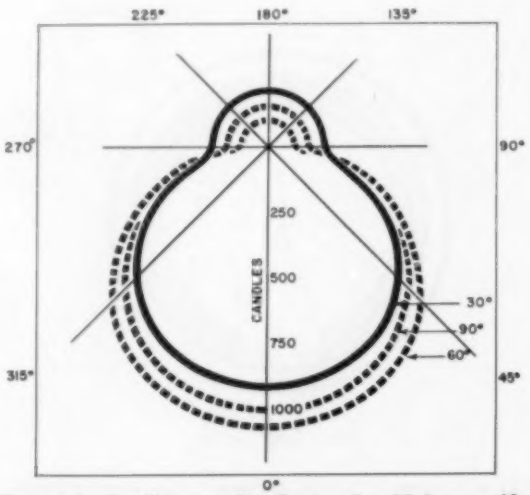


Figure 4. Candlepower distribution for 30-degree, 60-degree and 90-degree aperture angles.

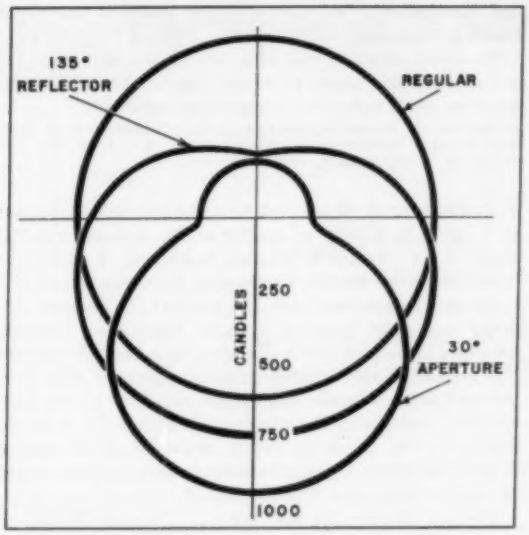


Figure 5. Candlepower distribution for 30-degree aperture lamp, 135-degree reflector lamp and regular extra-high-output lamp.

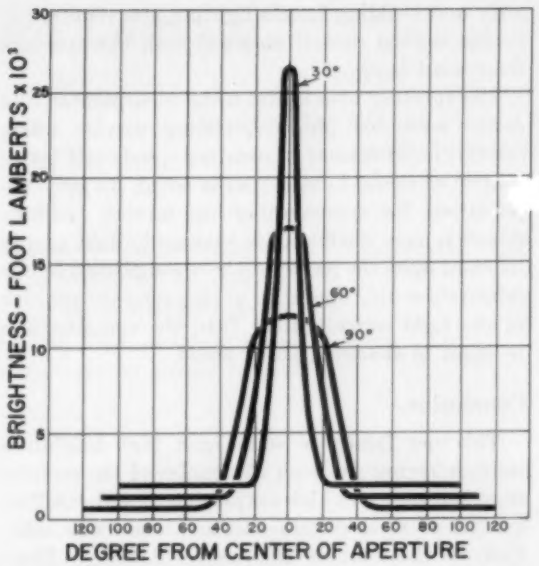


Figure 6. Brightness distribution for 30-degree, 60-degree and 90-degree aperture angles.

Comparison of the candlepower distribution for 30-, 60- and 90-degree aperture angles is shown in Fig. 4. Measurements were made at a distance of 20 feet with a photocell and microammeter. These data show that the maximum candlepower peaks somewhere in the region of $\alpha = 60$ degrees. Fig. 5 shows a comparison of the candlepower distribution of three extra-high-output fluorescent lamps; a 30-degree aperture lamp, a 135-degree reflector lamp and the regular extra-high-output lamp. These data show the advantages of small, high brightness, directional fluorescent sources over the conventional relatively large area, low brightness, fluorescent sources for applications necessitating precise lumen control.

Fig. 6 shows the brightness distribution of the 30-degree aperture lamp compared with lamps having 60- and 90-degree apertures. The extremely high brightness and sharp aperture cutoff obtainable with the 30-degree aperture are in evidence here. It also shows how the brightness and cutoff decrease rapidly with increasing aperture angle. Fig. 7 is another representation of the data shown in Fig. 5 and, in addition, shows that the reverse brightness increases with decreasing α. Measurements were made with a Pritchard Brightness Meter having 0.1-degree acceptance angle.

Applications

The aperture fluorescent lamp can be used where narrow beam width and high beam candlepower are necessary to produce a controlled distribution of light flux. In applications where it is essential that all the light be directed below a chosen cutoff, such as in highway and runway lighting, the aperture fluorescent lamp is especially useful. Details of the application of this source to luminaire design are given in a companion paper.[2]

Edge lighting of signs, lighting of ceilings and

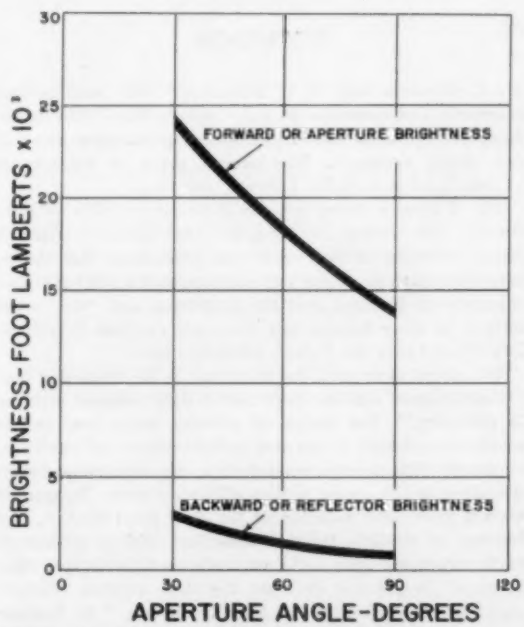


Figure 7. Forward and backward brightness rs aperture angle.

walls and building facade lighting also require the precise optical control obtained with the aperture fluorescent lamp.

The aperture idea is also being incorporated into lamps used for photoduplicating service where marked improvement in printing speeds and better control of useful light output is noted. In some applications for photoduplicating service, machine design is more flexible since changes in light energy incident upon the paper can be accomplished by the relatively simple operation of changing the position of the light source rather than the complications incident to changing paper speed.

Conclusions

This new family of small area, high brightness sources having the high efficiencies of the circular cross-section extra-high-output lamps and excellent control of light distribution are a welcome addition to the field of fluorescent lighting. These sources provide more useful light without sacrifice in efficiency and will allow the luminaire designer more precision in his optical design. The applications of the lamp are many and provide architects and engineers with a new tool for their designs of the future.

References

1. Spencer, D. E. and Montgomery, L. L.: "Interflections in Aperture Lamps," ILLUMINATING ENGINEERING, Vol. LVI, No. 3—Section II, p. 231 (March, 1961).
2. Peek, S. C.: "Aperture Lamps . . . Applied," a paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa.

DISCUSSION

M. A. CHERNIN AND H. C. FROELICH:* We have several comments and questions on the aperture lamp. The statement in regard to the brightness using phosphor alone is not clearly expressed. The number given in the text is 12,000 fL whereas Table I lists 22,000 fL.

Fig. 2 shows a strong increase of brightness with reflector density. The commercial lamp has been designed near the lower extremity of this curve. In support of this choice, some discussion should be provided concerning the important interrelation between aperture brightness and total lumen output, or other reasons why the lower aperture brightness is preferred over the higher, attainable ones.

We cannot agree with the statement in the conclusion that "these sources provide more useful light without sacrifice in efficiency." The design of reflector lamps now on the market loses nearly 15 per cent in light output and efficiency, compared with normal designs. The aperture lamp design described in this paper suffers additional losses because of wasted ultraviolet radiation at the clear glass window, and because of multiple internal reflections with some loss at each reflection. Our tests on aperture-type lamps show losses of 30 per cent or more, for these reasons. Figs. 8 and 9 of "Interflections in Aperture Lamps," by Spencer and Montgomery,[1] also indicate that losses of this order should be expected.

We would conclude that this serious loss will limit the use of aperture lamps to highly specialized applications requiring small reflectors and/or sharp cutoffs.

1. Spencer, D. E. and Montgomery, L. L.: "Interflections in Aperture Lamps." ILLUMINATING ENGINEERING, Vol. LVI, No. 3—Section II, p. 231 (March, 1961).

C. E. SWANSON:* It is noted from the data presented that an increase in density or opacity of the reflector material results in an increase in aperture brightness. I would like to ask the author whether any measurements were made with a reflector approaching complete opacity, and whether this would materially improve aperture brightness. External reflectors of various shapes and sizes have been utilized for this purpose in the industry. Have comparative data been obtained between inside and outside reflectors of the same opacity? Concerning the curve of Brightness *vs* Reflector Density in Fig. 2, can the author provide some relationship between the arbitrary units of density chosen and the weight of titanium oxide in a four-foot lamp?

The data showing the need for a special glass because of the unprotected portion of the aperture raises an interesting point. It is known that certain glasses, such as lead and various hard glasses, resist the activity of the mercury arc to a certain extent. Would the author be able to provide a brief explanation of the actual mechanism involved in the discoloration of lime glass as against other glasses? Is this due to the shorter wave length excitation, such as the 1840 Å line, or does the 2537 Å line play a more important part? The maintenance curve of the special glass shows a marked improvement over the regular lime glass even though there appears to be a depression in the initial zero hour output. Will the author elaborate as to the nature of the special glass and how this inhibits discoloration?

Finally, has any consideration been given to the use of higher loading, such as 50 watts per foot, rather than the normal 25 watts per foot of the present VHO lamp?

C. L. TOOMEY:** The figure given in Table I for the forward brightness of a 30-degree aperture lamp (22,000 footlamberts) is the brightness obtained when a reflector coating of phosphor (fines) is used in addition to the regular phospher coating. The 12,000-footlambert figure is for a 30-degree lamp using a single layer of regular phosphor coating.

In regard to reflector density, it is obviously desirable to use a high-density coating, but such coatings are difficult to process at normal production speeds. Much progress is being made on new process techniques.

So far we have not found a material as effective as titanium dioxide for use as reflector coating material. Flashed aluminum coatings, on both the inside and outside surface of the bulb, are less effective. With respect to a reflector coating approaching 100 per cent efficiency, calculations show that forward brightness could be almost doubled by substituting a material with 95 per cent reflectance for the present material, which is about 90 per cent effective. Such a material has not been found.

We agree that the aperture lamp has somewhat lower total lumen output than has the standard extra-high-output lamp. We feel, however, that more "useful" light output is obtained at high efficiency because better utilization of light output can be achieved with a narrow line source in luminaires of moderate size.

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**Author.

Interflections in Aperture Lamps

By DOMINA EBERLE SPENCER
L. L. MONTGOMERY

Through a theoretical formulation of the interflection problem in fluorescent lamps in terms of an integral equation and the solution to this equation, this paper shows how fluorescent lamps many times brighter than normal are possible, with no increase in power input.

As is well known, the advent of the fluorescent lamp was a great step toward the production of better visual condition in general lighting. For special applications, however, the advantages of the conventional lamp may become disadvantages. In particular, if a narrow beam is to be obtained, the large area of the fluorescent lamp offers a severe handicap when compared with the incandescent lamp. Ordinary fluorescent lamps are admirably suited to a structure such as a luminous ceiling, where no control of the light output is attempted. But for a device requiring sharp control, such as the automobile headlight, present fluorescent lamps are entirely inadequate.

A mathematical study of interflections within fluorescent lamps shows that the lamp suitable for applications requiring sharp control has a long, narrow, transparent slit or aperture. The photometric characteristics of aperture lamps are predicted:

(a) Within the aperture the lamp may be several hundred per cent brighter than conventional fluorescent lamps which are operated at the same power input,

(b) With suitable reflecting materials, a major part of the luminous output of the aperture lamp is radiated through a very narrow slit.

Thus, aperture lamps provide a very bright, narrow, one-sided source of light and open up a wide range of new applications.

Lamps based on this theory have been constructed. A brief description was given in a paper[1] presented to the Optical Society last October. A companion paper[2] at this Conference describes the construction of aperture lamps and the photometric characteristics hitherto obtained in actual lamps.

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. Authors: University of Connecticut, Storrs, Conn., and Sylvania Electric Products Inc., Salem, Mass.

This paper is devoted to the theoretical formulation of the interflection problem in fluorescent lamps in terms of an integral equation and the solution of this equation. The photometric characteristics obtainable with optimum materials are described. An understanding of the results of this investigation is needed by both lamp manufacturer and luminaire designer in order to realize the full potentialities of the aperture lamp.

It is hoped that the aperture lamp will be employed in a broad range of applications: automobile headlights, floodlighting of runways, bridges, walls, ceilings, low-mounted and high-mounted street lighting, cove lighting, indirect lighting, and even in the design of shallow luminous ceilings and luminous walls. Some of these applications are described in a companion paper.[3]

In this paper, the theoretical possibilities of control with the aperture lamp are illustrated by presenting a summary of the characteristics of a family of reflector-lamp combinations described in a paper[4] presented to the Optical Society last April. While the previous paper employed an exact specification of the characteristics of the family, this paper identifies a luminaire by giving the effective height of an equivalent rectangular source as a function of angle, in agreement with the new photometric methods suggested for photometry of fluorescent luminaires.[5] It is shown that fluorescent luminaires with beam widths from a fraction of a degree up to nearly 60 degrees are members of this family.

Interflections in Conventional Fluorescent Lamps

First consider the interflection problem in a very long cylindrical fluorescent lamp with a uniform coating of phosphor (Fig. 1a). It will be assumed that this phosphor layer acts as a perfectly diffuse surface to both reflected and transmitted light. The

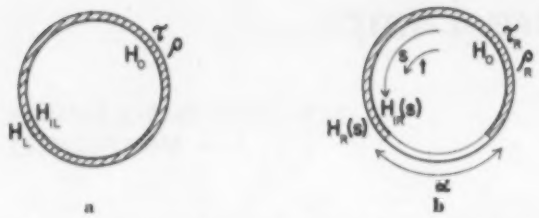

Figure 1. Cross sections of very long fluorescent lamps. (a) Conventional fluorescent lamp completely coated with phosphor, (b) Aperture lamp with transparent window subtending angle α at center of lamp.

ultraviolet light radiated by the mercury arc is absorbed in a very thin layer on the inside of the phosphor coating. Since the attenuation coefficient in the visible is only 0.003 times the attenuation coefficient in the ultraviolet, the appearance as viewed from either side is as though all the visible light were radiated from an infinitesimal layer on the inside of the phosphor coating. This layer is covered by a diffuse layer having reflectance ρ and transmittance τ for visible light. If there were no interflections, and the radiating layer could be viewed in free space from either side, it would have an initial helios H_o (brightness, if defined in terms of a converging lightcone at the receiver). The appearance of the inside of the lamp, including interflections, is specified by H_{IL}, while the appearance of the outside of the lamp is specified by H_L. The number of lumens per unit area incident on the inside of the phosphor surface is called D. By symmetry H_o, H_L, H_{IL} and D are independent of angle.

The fundamental equations, in which the effect of H_o is added to the effect of interflected light, are

$$H_L = \tau H_o + \tau H_{IL},$$
$$H_{IL} = D = H_o\,(1+\rho) + \rho\, D. \qquad (1)$$

Solving these simultaneous equations, we have

$$H_{IL} = D = \frac{H_o\,(1+\rho)}{1-\rho},$$
$$H_L = \frac{2\,\tau\,H_o}{1-\rho}. \qquad (2)$$

The total number of lumens radiated from a circular-cylinder lamp of radius a and length l is

$$F_L = 4\,\pi\,a\,l\,H_o. \qquad (3)$$

In most phosphors, losses are very low. Practically all of the visible light is either reflected or transmitted. If it is assumed that there are no losses,

$$\tau = 1 - \rho, \qquad (4)$$

and from Equation (2)

$$H_L = 2\,H_o \qquad (5)$$

and

$$\frac{H_{IL}}{H_L} = \frac{(1+\rho)}{2\,(1-\rho)}. \qquad (6)$$

In Fig. 2, H_{IL}/H_L is plotted versus reflectance ρ from Equation (6). If the reflectance is less than ⅓, the outside of the lamp is brighter than the inside. But for reflectances greater than ⅓, the inside of the lamp (which cannot be viewed directly in a completely coated lamp) is brighter than the outside of the lamp. In typical conventional fluorescent lamps, the reflectance is about 0.50 and the inside of the lamp is 1.50 times as bright as the outside. For higher reflectances, this value increases sharply. At $\rho = 0.90$, $H_{IL}/H_L = 9.50$; at $\rho = 0.95$, $H_{IL}/H_L = 19.5$ while at $\rho = 0.99$, $H_{IL}/H_L = 99.5$.

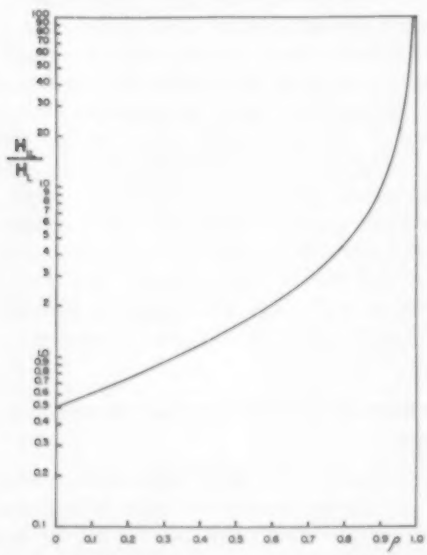

Figure 2. Ratio of H_{IL} to H_L versus reflectance, for conventional fluorescent lamp, calculated from Eq. (6).

In a fluorescent lamp, the really bright surface is the inside of the lamp. But this surface is entirely concealed from view. The surface normally viewed is the dull back of the phosphor layer.

Note that all of the visible light generated in the phosphor layer is eventually radiated from the lamp if $\tau = 1 - \rho$. This is true whether $\rho = 0.50$ or 0.99. The foregoing analysis can be applied without modification to the visible light generated in the arc stream itself. Therefore, the color of the inside and outside of the phosphor layer will appear to be identical combinations of mercury spectrum and continuous phosphor spectra.

Interflections in Aperture Lamps

In an aperture lamp, the bright interior is visible through a transparent window. The aperture subtends an angle α at the center of the lamp, Fig. 1b.

The remainder of the lamp is covered with the best available reflective coating, on the inside of which is the usual phosphor coating. As before, ultraviolet from the mercury arc is absorbed in a very thin layer on the inside of the phosphor coating. The resultant helios (brightness, if defined in terms of a converging light-cone) of both sides of this layer without interflections is H_o. The reflector portion of the lamp, including both reflective coating and phosphor, has a diffuse reflectance ρ_R and transmittance τ_R. The appearance of the outside of the reflector portion is specified by $H_R(s)$ and that of the inside by $H_{IR}(s)$, where s is an angle (Fig. 1b).

The integral equations are

$$H_{IR}(s)=H_o(1+\rho_R)+\rho_R\int_{-(\pi-\alpha/2)}^{(\pi-\alpha/2)}K(s,t)H_{IR}(t)\,dt,$$
$$H_R(s)=\tau_R H_o+\tau_R\int_{-(\pi-\alpha/2)}^{(\pi-\alpha/2)}K(s,t)H_{IR}(t)\,dt. \tag{7}$$

From the unit-sphere method,[6] it is readily shown that the kernel is

$$K(s,t)=\frac{1}{4}\sin\left|\frac{s-t}{2}\right|. \tag{8}$$

Substitution of Equation (8) into Equation (7) gives

$$H_{IR}(s)=H_o(1+\rho)+\frac{\rho_R}{4}\int_{-(\pi-\alpha/2)}^{(\pi-\alpha/2)}H_{IR}(t)\sin\left|\frac{s-t}{2}\right|dt$$
$$=H_o(1+\rho)+\frac{\rho_R}{4}\left\{\int_{-(\pi-\alpha/2)}^{s}H_{IR}(t)\sin\left(\frac{s-t}{2}\right)dt + \int_{s}^{(\pi-\alpha/2)}H_{IR}(t)\sin\left(\frac{t-s}{2}\right)dt\right\}$$

or since

$$\sin\left(\frac{s-t}{2}\right)=\sin\frac{s}{2}\cos\frac{t}{2}-\cos\frac{s}{2}\sin\frac{t}{2}$$
$$\sin\left(\frac{t-s}{2}\right)=\sin\frac{t}{2}\cos\frac{s}{2}-\cos\frac{t}{2}\sin\frac{s}{2},$$

$$H_{IR}(s)=H_o(1+\rho)+\frac{\rho_R}{4}\left\{\sin\frac{s}{2}\int_{-(\pi-\alpha/2)}^{s}H_{IR}(t)\cos\frac{t}{2}\,dt - \cos\frac{s}{2}\int_{-(\pi-\alpha/2)}^{s}H_{IR}(t)\sin\frac{t}{2}dt+\cos\frac{s}{2}\int_{s}^{(\pi-\alpha/2)}H_{IR}(t)\sin\frac{t}{2}dt - \sin\frac{s}{2}\int_{s}^{(\pi-\alpha/2)}H_{IR}(t)\cos\frac{t}{2}\,dt\right\}. \tag{9}$$

If the solution of Equation (9) can be expressed in closed form, one would expect it to be a linear combination of trigonometric functions. From the symmetry of the problem, it is clear that the solution must be an even function of s. Thus, a reasonable assumption is

$$H_{IR}(s)=A+B\cos\frac{ks}{2}. \tag{10}$$

Now substitute Equation (10) into Equation (9) and see if A, B and k can be determined. The resulting values are

$$\begin{cases} k=\sqrt{1-\rho_R} \\ A=\dfrac{H_o(1+\rho_R)}{1-\rho_R} \\ B=-2H_o\rho_R\dfrac{1+\rho_R}{1-\rho_R}\sin\alpha/4\times \\ \left[(1+k)\cos\left(\dfrac{1-k}{2}\right)\left(\pi-\dfrac{\alpha}{2}\right)\right. \\ \left.+(1-k)\cos\left(\dfrac{1+k}{2}\right)\left(\pi-\dfrac{\alpha}{2}\right)\right]^{-1} \end{cases} \tag{11}$$

Since the constants can be determined uniquely, the solution of Eq. (10) is exact. Simplification gives the complete solution of Eq. (7) in the form

$$H_{IR}(s)=\frac{H_o(1+\rho_R)}{(1-\rho_R)}\left[1-\rho_R E\cos\frac{\sqrt{1-\rho_R}}{2}s\right], \tag{12}$$

$$H_{IRmin}=\frac{H_o(1+\rho_R)}{(1-\rho_R)}\,1-\rho_R E\quad, \tag{12a}$$

$$H_{IRmax}=\frac{H_o(1+\rho_R)}{(1-\rho_R)}\times \tag{12b}$$
$$\left[1-\rho_R E\cos\frac{\sqrt{1-\rho_R}}{2}(\pi-\alpha/2)\right],$$

and

$$H_R(s)=\frac{\tau_R H_o}{(1-\rho_R)}\left[2-(1+\rho_R)E\cos\frac{\sqrt{1-\rho_R}}{2}s\right], \tag{13}$$

$$H_{Rmin}=\frac{\tau_R H_o}{(1-\rho_R)}\left[2-E(1+\rho_R)\right], \tag{13a}$$

$$H_{Rmax}=\frac{\tau_R H_o}{(1-\rho_R)}\times \tag{13b}$$
$$\left[2-E(1+\rho_R)\cos\frac{\sqrt{1-\rho_R}}{2}(\pi-\alpha/2)\right],$$

where

$$E=2\sin\alpha/4\times \tag{14}$$
$$\left[(1+\sqrt{1-\rho_R})\cos\left(\frac{1-\sqrt{1-\rho_R}}{2}\right)(\pi-\alpha/2)\right.$$
$$\left.+(1-\sqrt{1-\rho_R})\cos\left(\frac{1+\sqrt{1-\rho_R}}{2}\right)(\pi-\alpha/2)\right]^{-1}$$

The total number of lumens radiated through the back of the reflector is

$$F_R=2\,a\,l\int_o^{\pi-\alpha/2}H_R(s)\,ds. \tag{15}$$

Substitution of Eq. (13) into Eq. (15) gives

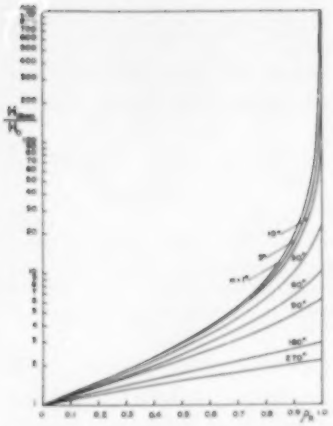

Figure 3. Ratio of H_{IRmin} to H_o versus reflectance ρ_R of reflector coating, for various aperture lamps whose openings subtend an angle α, calculated from Eq. (12a).

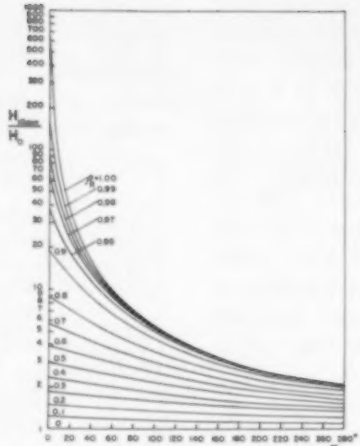

Figure 4. Ratio of H_{IRmin} to H_o versus aperture angle for various values of reflectance ρ_R, calculated from Eq. (12a).

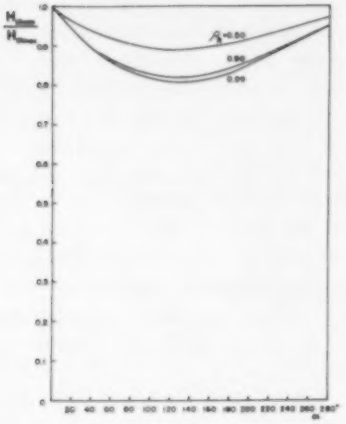

Figure 5. Ratio of H_{IRmin} to H_{IRmax} for inside of lamp as a function of aperture angle α and reflectance ρ_R, calculated from Eqs. (12a) and (12b).

$$F_R = \frac{4\,a\,l\,\tau_R\,H_o}{(1-\rho_R)}\left[(\pi-\alpha/2)\right. \tag{16}$$

$$\left. -\frac{E(1+\rho_R)}{\sqrt{1-\rho_R}}\sin\frac{\sqrt{1-\rho_R}}{2}(\pi-\alpha/2)\right].$$

The total number of lumens radiated from both sides of the phosphor is (assuming a perfectly diffuse radiator)

$$F = 4\,a\,l\,H_o\,(\pi-\alpha/2). \tag{17}$$

In the special case of no losses in the phosphor coating

$$\tau_R = 1-\rho_R \tag{18}$$

and

$$F = F_A + F_R, \tag{19}$$

where F_A is the total number of lumens radiated through the aperture. From Eqs. (16) through (19),

$$F_A = \frac{4\,a\,l\,H_o\,(1+\rho_R)\,E}{\sqrt{1-\rho_R}}\sin\frac{\sqrt{1-\rho_R}}{2}\;(\pi-\alpha/2). \tag{20}$$

However, since F_A depends only on ρ_R and α, and is entirely independent of whether there are losses in the phosphor or not, Eq. (20) holds whether Eq. (18) is satisfied or not. Also from Eqs. (17) and (20) we have, for a diffuse radiator,

$$\frac{F_A}{F} = \frac{(1+\rho_R)\,E}{\sqrt{1-\rho_R}\,(\pi-\alpha/2)}\sin\frac{\sqrt{1-\rho_R}}{2}\;(\pi-\alpha/2).$$

Theoretical curves of the ratio of H_{IRmin} to H_o, calculated from Eq. (12a), are shown in Figs. 3 and 4. The effect of interflections on raising the helios of the inside of the lamp is here illustrated. In Fig. 3, data are plotted as a function of the reflectance of the reflector coating ρ_R for lamps with various aperture angles α. These curves emphasize that for all apertures, the inside of the lamp becomes very bright when ρ_R approaches unity. In Fig. 4 the same data are plotted as a function of aperture angle for various values of reflectance ρ_R. At very high reflectances and at small aperture angles, a one-per cent change of reflectance may increase H_{IRmin} by amounts up to 400 per cent. Thus, for the brightest possible aperture lamp, small changes in reflectance have surprisingly large effects.

Equation (12) shows that, with a perfectly transparent aperture, the inside of the lamp does not appear to be uniform. It is brightest at the edges of the aperture and has its minimum at the center of the reflector coating. However, as shown in Fig. 5, this departure from uniformity is never large. For very large and for very small apertures, the inside of the lamp approaches uniformity. The non-uniformity is greatest for intermediate values of α and for very high reflectances. At $\alpha = 140$ degrees the maximum variation is still less than 20 per cent while at $\alpha = 30$ degrees it is always less than 10 per cent. If the window is made of glass (whose surface has not been coated to eliminate surface reflections), this variation may not be observable from outside the lamp. The maximum must be viewed at angles at which Fresnel reflections are large, while the minimum is viewed at angles at which Fresnel reflections are small.

Corresponding data on the non-uniformity of the

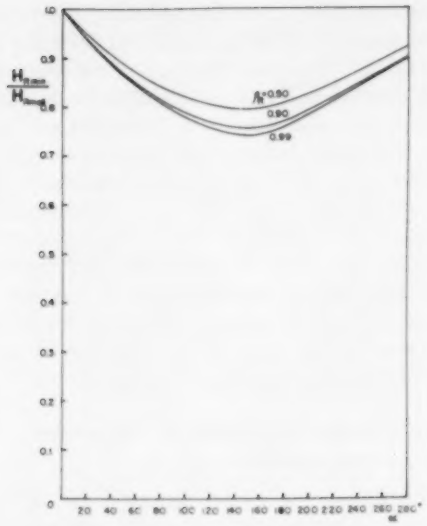

Figure 6. Ratio of H_{Rmin} to H_{Rmax} for outside of lamp as a function of aperture angle α and reflectance ρ_R, calculated from Eqs. (13a) and (13b).

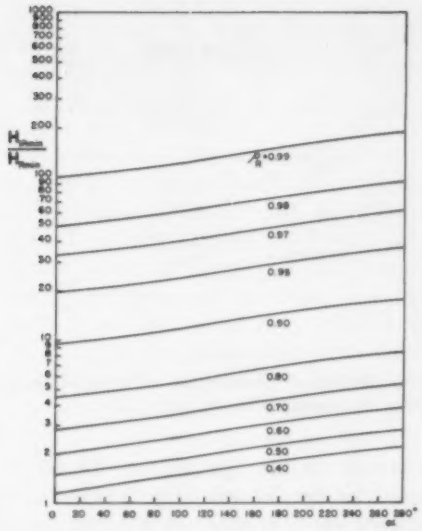

Figure 7. Ratio of H_{1Rmin} to H_{Rmin} as a function of aperture angle α for various values of reflectance ρ_R, calculated from Eqs. (12a) and (13a).

exterior of the lamp are shown in Fig. 6. Calculations are based on Eqs. (13a) and (13b). Qualitatively the effect is the same as for the inside of the lamp. However, the maximum effect is slightly larger, reaching 26 per cent.

Perhaps the easiest quantities to measure are H_{1Rmin} and H_{Rmin}. The ratio is plotted in Fig. 7, for the case in which there are negligible losses in the phosphor coating (where Eq. (18) is valid). Ratios of 10:1 are obtained if $\rho_R = 0.90$ and aperture angles are small. An increase of reflectance from 0.90 to 0.95 gives a ratio of at least 20:1. At $\rho_R = 0.98$, the ratio is at least 50:1; and for $\rho_R = 0.99$, it becomes 100:1 or better. By comparing measured values of H_{1Rmin}/H_{Rmin} at known α to Fig. 7, the equivalent reflectance of phosphor and reflector coating may be estimated. This method of determining ρ_R has the disadvantage that phosphor losses have been neglected.

The purpose of an aperture lamp is to produce

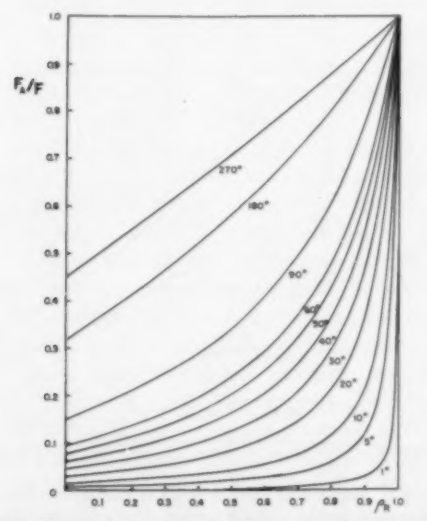

Figure 8. Fraction of phosphor lumens radiated through aperture as a function of reflectance of reflector coating ρ_R for various aperture angles α, calculated from Eqs. (17) and (20).

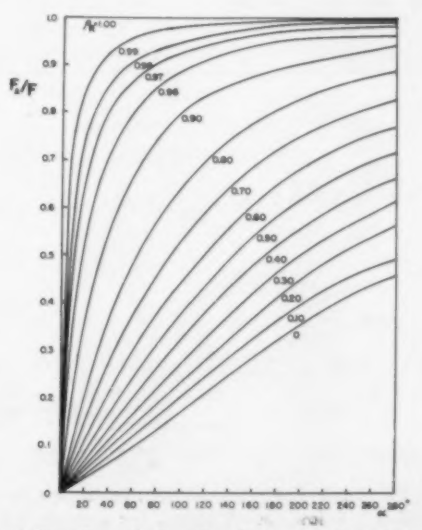

Figure 9. Fraction of phosphor lumens radiated through aperture as a function of aperture angle α for various reflectances ρ_R, calculated from Eqs. (17) and (20).

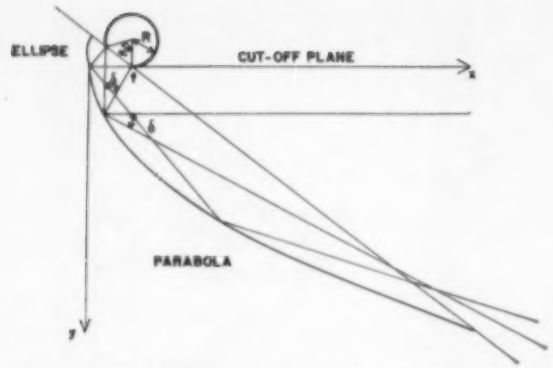

Figure 10. Reflector contours for a family of luminaires employing the aperture lamp.

the brightest possible light source. Therefore, the success of the lamp should be judged primarily on how large a value of H_{IR} can be attained. However, as conventional lamps are judged primarily on the number of lumens radiated, some study of this question for aperture lamps is also desirable. As the aperture lamp contains a smaller phosphor area than a conventional fluorescent lamp, the total number of lumens F emitted by the phosphor will be less than for a conventional lamp, by the factor $(1 - \alpha/2\pi)$.

A more interesting question is the fraction of the light radiated through the aperture window. From Eqs. (17) and (20), the ratio F_A/F was calculated. Results are shown in Figs. 8 and 9. In Fig. 8, the data are plotted versus ρ_R for various values of aperture angle. If a high value of F_A/F is to be attained, it is particularly important to employ very high values of reflectance. For $\alpha =$ 270 degrees and $\rho_R = 0.1$, half the light will be emitted from the aperture (and half from the back of the lamp). The same fraction is reflected when $\alpha = 90$ degrees and $\rho_R = 0.7$, when $\alpha = 30$ degrees and $\rho_R = 0.9$, and when $\alpha = 5$ degrees and $\rho_R = 0.985$. The same data are plotted versus aperture angle for fixed values of reflectance in Fig. 9. This figure shows that if the reflectance approaches 1.00, then all light is radiated through the aperture for all values of α. If $\rho_R = 0.99$, then F_A/F would be better than 0.90 for α greater than 30 degrees. But if $\rho_R = 0.97$, F_A/F exceeds 0.90 only for α above 76 degrees and for $\rho_R = 0.90$, F_A/F does not reach 0.90 until α is greater than 180 degrees.

Characteristics of a Family of Luminaires Using Aperture Lamps

A family of luminaires designed for aperture lamps was described in a previous paper.[4] These luminaires are designed to provide the sharp cut-off characteristic of macrofocal conics when combined with conventional fluorescent lamps.[7] The same type of control of fluorescent-lamp output can be obtained by placing one edge of the aperture lamp at the focus of a specular parabolic-cylinder reflector as shown in Fig. 10. If the reflector is extended until it intersects the plane through the edges of the aperture, then all the light emitted through the aperture will be reflected into the useful beam of light. The light which strikes the parabolic reflector will be reflected into a beam subtending an angle δ whose upper edge is always parallel to the cut-off plane. The elliptic reflector at the top has its foci at the two edges of the aperture and reflects light into the aperture. For

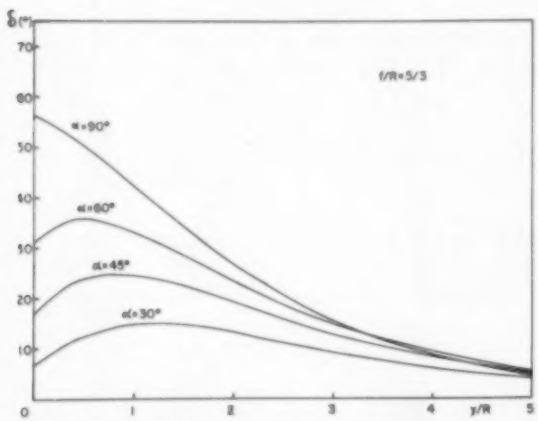

Figure 11. Angle δ of reflected light beam as a function of distance y below cut-off plane, for a single reflector with $f = 5/3\ R$ and 30-, 45-, 60- and 90-degree aperture lamps.

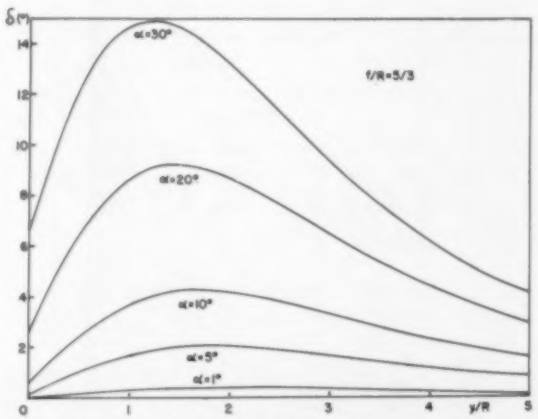

Figure 12. Angle δ of reflected light beam as a function of distance y below cut-off plane, for a single reflector with $f = 5/3\ R$ and 1-, 5-, 10-, 20-, and 30-degree aperture lamps.

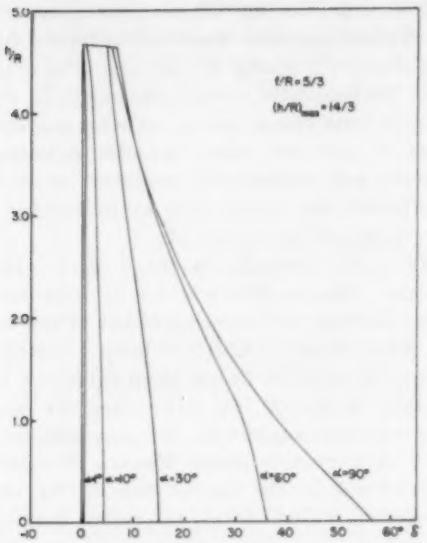

Figure 13. Effective height h of equivalent rectangular source versus angle δ below cut-off plane for $f/R = 5/3$ and $(h/R)_{max} = 14/3$, for aperture angles from 1 to 90 degrees. Applicable for all points $y \geq y_{max}$ of reflector.

perfectly sharp cut-off, no light should be emitted through the back of the lamp. However, good results can be obtained even if considerable light is transmitted through the phosphor if suitable baffles are employed.[3]

This family of luminaires has an advantage over the macrofocal family.[7] Suppose an aperture lamp is three times as bright as a conventional fluorescent lamp of the same power input. This advantage can be used in either of two ways: by reducing the size of the reflector by a factor of three or by reducing the power input by a factor of three. In either way the aperture lamp provides greater economy in controlled lighting.

It was shown previously,[4] that the output from the reflector family of Fig. 10, can be determined from a knowledge of the angle δ of the reflected beams at each point along the reflector contour. Position of points on the contour is specified by the distance y below the focal plane of the parabolic reflector. The lamp radius is R and the focal length of the parabola is f. Figs. 11 and 12 show values of δ versus y/R for a reflector with $f/R = 5/3$ and various aperture angles. For $\alpha = 90$ degrees, the entire reflector is filled for small values of δ. As the angle below the cut-off plane is increased, the width of the reflector that is filled with an image of the aperture decreases and gradually disappears at the top of the parabolic reflector. However, for smaller aperture angles, as δ increases, both top and bottom of the reflector become dark and the image finally disappears at some distance from the top of the reflector. For instance, at $\alpha = 30$ degrees, the image finally disappears at a distance y/R slightly greater than 1.

A more convenient specification is obtained by determining the range of values of y for which δ is grater or equal to a given value and multiplying by cos δ. This is the height h of an equivalent rectangular source in a plane perpendicular to a given direction δ below cut-off plane. This specifies the resulting distribution of light received at any point which is below a plane parallel to the cut-off plane and passing through the bottom of the parabolic reflector. Fig. 13 shows a plot of height of the equivalent rectangular source as a function of angle δ below cut-off plane for a reflector whose maximum width is 14/3 times the lamp radius. A variety of curves of h versus δ are obtained with a single reflector, by merely interchanging aperture lamps.

To the illuminating engineer, accustomed to visualize luminaire characteristics in terms of candlepower distributions, Fig. 14 may be more meaningful. It is a polar plot of the data of Fig. 13. At very large distances from the luminaire, a plot of h versus δ has the same shape as a candlepower distribution curve. It has, however, the advantage that, whereas a single candlepower curve cannot be used at all distances from the luminaire, a single curve of h versus δ can be expected to be significant at all distances. This entire family of luminaire characteristics are obtained with a single reflector and a variety of aperture lamps. Other combinations can be obtained with other values of f/R.

Fig. 15 shows two of the curves of Figs. 13 and 14

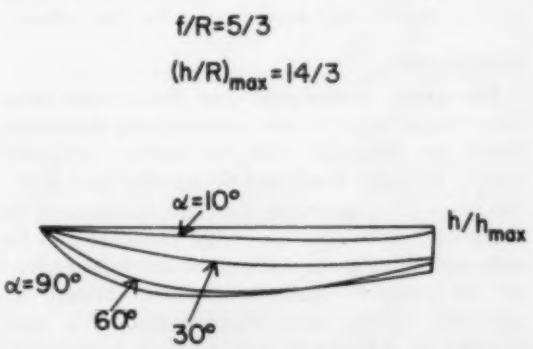

Figure 14. Polar plot of h/h_{max} versus δ. This curve has the same shape as a candlepower curve measured at very large distances from the luminaire, yet is significant at all distances.

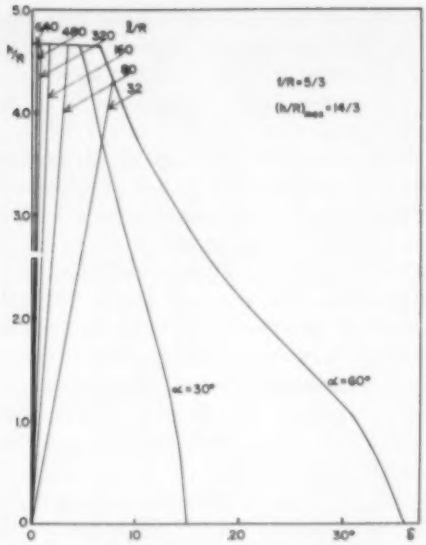

Figure 15. Plot of effective height of reflector as a function of δ, for various distances l to the receiver. Except for small values of δ, the same curve of h versus δ is obtained at all distances.

plotted to a larger scale and with additional data on the effect on h of the distance l from the luminaire at which measurements are made. In the region between the cut-off plane and the plane parallel to the cut-off plane through the bottom of the luminaire, only that part of the reflector which is above the receiver will appear filled with an image of the aperture. Thus, in this region, h first increases nearly linearly until it reaches the curves of Fig. 13 and then follows them at larger values of δ. Thus, if the effective height of the reflector is measured as a function of δ at various distances l, the curves can be expected to increase along different sloping lines for different values of l, but follow the same curve after the y-coordinate of the receiver exceeds y_{max} for the reflector.

Conclusions

The paper has shown that fluorescent lamps many times brighter than conventional fluorescent lamps are attainable with no increase in power input. This gain is effected by interflections within the lamp. The maximum that can be obtained depends on the reflectances of the phosphor and the reflector. With $\rho_R = 1.00$, all of the light emitted by the phosphor would be radiated through the aperture. As this limit is approached, very small changes in reflectance will produce surprisingly large changes in H_{IR} and F_A/F.

The paper has also described a family of reflectors that employ aperture lamps to provide controlled fluorescent with no light above a given cut-off plane and with beam widths from a fraction of a degree to nearly 60 degrees. The extent to which the calculated characteristics can be realized depends upon opaqueness of reflector coating, precision of aperture edges, specular reflectance of reflector, and accuracy of luminaire construction. It is hoped that many other applications of aperture lamps will be developed.

We wish especially to thank S. C. Peek of Sylvania Electric Products for his continual aid, understanding, and encouragement in the theoretical development of aperture lamp principles and for the opportunity to test these principles experimentally within a few days after the aperture lamp was first suggested. We also wish to thank Keith Butler of Sylvania Electric Products for material aid in the formulation of the physical assumptions on which this theoretical development is based.

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DISCUSSION

J. B. DE BOER:* As to the subject of this paper, as well as to those by Messrs. Toomey[1] and Peek,[2] I cannot help but feel some surprise that the so-called aperture lamps were announced in the United States last year and again even now as new light sources. As early as 1955, my colleagues Mr. Balder and Mr. van de Weyer[3] gave full details of the possibilities of tubular fluorescent lamps provided with a reflecting layer on a part of the circumference of the cross section of the lamp only. This does not by any means minimize my appreciation for the authors' very complete theoretical presentation of the physical limits of the possibilities of these lamps as well as of the features to be obtained by the combination of properly designed aperture lamps and reflector luminaires.

I doubt, however, whether the application possibilities of these lamps are really as great as the enthusiasm of the authors might lead us to expect.

*N. V. Philips' Gloeilampenfabrieken, Eindhoven, Netherlands.

I can hardly believe, for instance, that aperture lamps are to be considered as a serious proposition for automobile headlights, unless luminances at least ten times higher than the ones mentioned in the paper (22,000 fL) become available; notwithstanding the theoretical possibility, I very much doubt this because of the practical limitations of the available materials.

I do not deny that, both in roadway lighting and in lighting the landing mat of a runway, aperture lamps in well-designed reflectors show a number of very promising features. What I miss so far in the published information on these applications is how the surfaces to be lighted look when they are wet. On curves the luminance will be even better and more uniform than when dry. On straight stretches of road and runways, however, only rough and well-drained surfaces will render satisfactory results.

When we introduced these lamps in 1955, the possibility of considerably reducing the light loss due to dirt in interior lighting by applying reflectorized lamps with the slit downward proved to be one of the major features of the application. Lamps of this type could, furthermore, make all those installations efficient where little or no reflection from ceilings or deteriorated luminaires was to be expected. For further details, refer to the publication by Messrs. Balder and van de Weyer.[3] In view of this field of application (interior lighting), we chose an aperture giving the maximum downward intensity with acceptable loss in total luminous flux and without loss in color rendering properties. A good value proved to be a slit width of roughly one third of the circumference of the lamp. With such a wide slit without fluorescent coating, the light emerging directly from the mercury-vapor discharge would give a nonacceptable distortion of the color rendering in interiors. For this reason we only introduced lamps provided with a fluorescent coating covering the entire inner surface.

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B. F. JONES:* The authors present the mathematics behind the characteristics of aperture lamps. These characteristics lead to the attainment of very high brightness sources, which should be of great use in controlled lighting using linear sources.

The computations made by the authors are of particular interest to me, since the problem is one which is particularly adaptable to solution by means of the Luminous Analog Computer. The limited checks I have been able to make to date have confirmed the results obtained analytically by the authors for the case of no losses in the phosphor.

In this mathematical treatment, the authors assume no losses in the system. This is done primarily to simplify the mathematics involved. This assumption is undoubtedly justifiable so far as the phosphor layer is concerned; it is my understanding, however, that commercially available lamps have, in addition, a reflective coating under the phosphor to raise the interior reflectance of the lamp and therefore raise its aperture brightness. Is it justifiable to neglect the losses in this coating and in the glass of the lamp itself? If not, the ratios of internal to external helios will not be valid; rather, they should be generally somewhat higher than those given.

It is stated that equation (20) is valid whether or not there are losses in the phosphor. This is quite true, but it should not be inferred from this that the ratio F_A/F, given in the next equation and plotted in Fig. 9, is applicable to the lamp itself. In practice, F_A will be of the magnitude calculated by equation (20), less losses incurred in passing through the glass, but F_R will be reduced substantially by losses in the reflective coating and the glass. As a result, for a practical lamp, the ratio of F_A to F will be somewhat larger than for the phosphor alone, as plotted in Fig. 9. The equation for F_A/F can be modified to take these losses into account, at the cost of considerable additional complexity. If this were done, and actual values of the reflectances and transmittances for practical lamps were given, it would be of interest to see how closely the ratios agree with those measured on an actual lamp.

M. A. WEINSTEIN:* The authors make the simplifying assumption that the ratio of inside to outside generated brightness (*i.e.*, brightness without interflections) is $(1 + \rho)/\tau$. According to available data, this is a considerable overestimate of the true value of this important ratio.

How uniform is the aperture lamp near the ends? The calculation in the paper assumes, of course, that the lamp is infinitely long, so that end effects can be neglected. Actually, however, since the base and cathode structures in standard lamps absorb a large fraction of the light striking them, the brightness of the aperture lamp must decrease near the ends, and must rise to the calculated value only when the distance from the end is large enough so that the amount of generated light reaching the end is negligible. Obviously, the greater the reflectance and the smaller the aperture angle, the greater this distance will be, so that one would expect the end loss effect to be quite important in high-reflectance, narrow aperture lamps. For example, in the limit of vanishing aperture angle one finds, using the exponential approximation to the interflection kernel for a cylinder of finite length, that with a reflectance of 99 per cent one must go about 23 tube diameters from the end before the internal brightness rises to 99 per cent of its limiting value. For a 48T12 lamp, this would give a net emission about 30 per cent smaller than that calculated in the paper, and for smaller ratios of tube length to tube diameter the end loss would be even greater. What is found in practice?

D. E. SPENCER AND L. L. MONTGOMERY:** The comments of the discussers provide an opportunity to clarify several points not discussed in the paper.

For Dr. de Boer we would like to explain the marked difference between the reflector lamp and the aperture lamp, which are two entirely distinct lamps. The reflector lamp is coated with the normal fluorescent powder over the entire surface. The aperture lamp, on the other hand, has a transparent window, on which there is no phosphor coating. This window allows one to see the bright interior of the lamp, thus providing an exceedingly bright, narrow, uniform source of light. Consequently, the aperture lamp opens up a whole new field of applications where its narrow opening allows control of the light distribution.

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**Authors.

The reflector lamp was introduced in the Netherlands by N. V. Philips' Gloeilampenfabrieken and is also manufactured in this country. According to Messrs. Balder and von de Weyer, "the 'TL'F lamp is coated over a fraction f of its circumference (*viz.*, the so-called "slot") with normal fluorescent powder only, whilst on the remainder of the circumference, a layer with good reflection characteristics is applied under the fluorescent powder layer."[1]

The purpose of the reflector lamp is merely to provide a slightly greater downward component in industrial luminaires. The Dutch authors state, "In the case of the newly developed 'TL'F lamp . . . fouling has much less influence than with the usual lamp types. . . . It is thus possible to mount the lamp in such a way that only a relatively small proportion of the light is radiated upwards. A layer of dirt on the top of the lamp then has only a very slight influence on the total luminous flux radiated."[1] Obviously, this idea is completely different from the function of the aperture lamp.

The purpose of the aperture lamp is to produce a very bright, narrow, uniform source which, when combined with a reflector or refractor, gives a controlled distribution of light. To do this we do two things: we go to the brightest fluorescent light source available—the inside of a highly reflecting lamp—and we utterly remove the impeding veil of phosphor (used in the reflector lamp) and view the inside of the lamp directly. The aim of the aperture lamp is to produce *high helios*.

The aperture lamp, even as currently manufactured, gives a uniform, fluorescent source of light which is several hundred per cent brighter than any previously available fluorescent lamp. It makes possible the development of an entirely new family of controlled fluorescent luminaires for both interior and exterior lighting.

Aperture lamps have already been given preliminary road tests as automobile headlights on a specially equipped automobile. As presently manufactured they show promise of being competitive with low beam systems and can have the twin advantages of reduced glare and superior illumination. Mr. Peek, who has driven an automobile equipped with aperture luminaire headlights several hundred miles, reports that they are an effective system and that the added light on the sides of the road from the broad horizontal beam gives a sense of added confidence.[2]

Field inspection of wet roadways lighted with low-mounted aperture luminaires gives the impression of daylight illumination of the pavement even in rain.

Dr. de Boer seems to imagine that the mercury-vapor spectrum will distort the color of the light from an aperture lamp. Detailed analysis shows that the output of either the reflector lamp or the aperture lamp will contain mercury lines. These will escape either by reflection or by transmission. Their proportion in the emergent radiation is almost exactly the same for either type of lamp.

In reply to Mr. Jones' comments, we would like to clarify the effect of absorption on the output of aperture lamps. The solution of the interflection problem was originally worked out for arbitrary reflectance ρ, transmittance τ, and absorptance α. However, it was noted that the helios of the aperture depended only on ρ while the helios of the dark side of the reflector H_R depended on both ρ and τ. At the suggestion of Dr. Keith Butler of Sylvania Electric Products Inc., it was decided to reduce the number of parameters by making the assumption that $\tau=1-\rho$. Absorptance in the phosphor is believed to be less than two per cent. As the transmittance does not enter into the multiple reflections, the solution is not sensitive to small changes in absorptance. Our results for H_A and F_A are independent of the value of α; the values for H_R and F are in error by less than two per cent.

The foregoing estimates also hold for the reflecting coatings. For example, with a very thick layer of titanium dioxide, the reflectance approaches 98 per cent. Therefore, the sum of absorptance and transmittance is two per cent even for a highly reflecting material. Both phosphor layer and the reflecting layer scatter the light rather than absorb it. Our assumption of negligible losses is believed to be valid for both cases to the accuracy of photometric measurements. Losses on passing through the glass are the usual Fresnel type encountered at all untreated glass surfaces. These may be eliminated by the use of thin film coatings if desired.

Dr. Weinstein questions our assumption that the light may be considered to be generated in a thin layer of infinitesimal thickness on the interior of the phosphor. To justify this assumption, a more exact expression was worked out but only the result was included in our paper. Consider that the attenuation coefficient is α_V in the visible region and α_U in the ultraviolet. Also consider the light generated in a layer of thickness dx at a distance x from the inside of the phosphor layer is directly proportional to $e^{-\alpha_U x}$. To be seen on the outside of the lamp, with phosphor thickness l, this radiation is further attenuated by $e^{-\alpha_V (l-x)}$; to be seen on the inside by $e^{-\alpha_V x}$. Integration over the entire thickness of the phosphor gives a ratio of

$$\frac{H_{OL}}{H_O} = \tau \left[\frac{\alpha_U + \alpha_V}{\alpha_U - \alpha_V}\right]\left[\frac{e^{-(\alpha_U - \alpha_V)l} - 1}{e^{-(\alpha_U + \alpha_V)l} - 1}\right]$$

where H_{OL} is the helios as viewed from the outside without interflections and H_O is the helios as viewed from the inside without interflections and $\tau = e^{-\alpha_V l}$. For actual phosphor coatings, a representative value is $\alpha_V = 0.003\ \alpha_U$, so the above expression is essentially $H_{OL}/H_O = \tau$ to within less than one per cent error. Thus our assumption is justified.

Dr. Weinstein also points out that the lamp is not strictly uniform throughout its length. This is, of course, true for all fluorescent lamps. It is a variation that is ordinarily neglected—and rightly so. Experimental measurements on present aperture lamps have shown that this variation is actually less than ten per cent (except in the last four inches near the heat shield and socket). Thus the lamp is uniform to within the accuracy of most photometric measurements.

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Design and Performance of an Inset Runway Light

By C. H. LOCH

The need for giving pilots better guidance in the touchdown areas of a runway has resulted in the placement of lights directly in the runway pavement. The optimum of a completely flush light, which removes all hazard to aircraft, works directly against the optical requirements of some exposed area, which can be seen from far down a runway. This paper discusses optical design requirements and their compromise with mechanical and electrical requirements of such a light.

THE NEED for better runway lighting has become more acute with each increase in airplane size and speed and has been brought into sharp focus by the presence of jets. This need is one of giving the pilot better guidance in the touchdown area of a runway.

Over the years there have been many improvements in airport ground lighting. Runway edge lighting has seen the development of three different types of lights to do the job of outlining the edges of the runway area. Several different types of approach lighting systems had been tried before the adoption as a national standard of the centerline approach system, with its sequenced flashing condenser discharge lights.

These improvements have served also to point up the need of better guidance in the landing or touchdown area of the runway. This is the area where an airplane's wheels make their initial contact with the pavement surface. It is the area which at night is referred to by pilots as the "black hole" because of the absence of lights.

Two radically different approaches have been tried toward solving this problem of lighting in the touchdown area of a runway. One is floodlighting the runway surface by edge-mounted floodlights. The other is by the placement of a configuration of signal lights in the touchdown area.

Floodlighting the runway surface is currently being tried and tested using fluorescent floodlight luminaires. The optical design of such a luminaire was reported at the 1958 IES Conference in Atlanta.[1] More recently, tests are being run at National Aviation Facilities Evaluation Center using 200-watt incandescent floodlights.

It has been generally agreed that floodlighting the runway surface does a good job in clear weather conditions at night. Some controversy centers around the question of its satisfactory use in marginal and bad weather.

The other approach toward providing guidance in the runway touchdown area is to place a configuration of signal lights in the runway pavement.

A signal light, as contrasted to a floodlight, is a light which points toward the observer and provides information to the observer by virtue of its color and/or its relative position to other lights. Such lights are used for all present-day airport ground lighting and are used in the concept of narrow gage lighting. Narrow gage lighting is just what the name implies, two rows of signal lights straddling the runway centerline, with the rows comparatively close together. This configuration places the lights in the pilot's direct foveal vision so that they may be seen more easily and better define the touchdown area of a runway.

This concept is being installed at several airfields for testing and evaluation. The most thorough early tests have been reported by the United States Air Force in the installations at Dow and Westover Air Force Bases.[2] The FAA has a test installation at its National Aviation Facilities Evaluation Center at Atlantic City and the New York Port Authority has made an installation at Idlewild.

As a result of the development of the narrow

A paper presented at the National Technical Conference of the Illuminating Engineering Society, September 11-16, 1960, Pittsburgh, Pa. AUTHOR: Westinghouse Electric Corp., Cleveland, Ohio.

gage concept, there has also emerged the need for light patterns in the runway beyond the touchdown area.

One such need has resulted in a row of lights down the runway centerline to better guide the pilot during the aircraft's deceleration and roll out.

It has also become desirable from the operations standpoint of jet aircraft to guide the plane off the runway into a taxiway as soon as possible after after touchdown and, therefore, while the plane is still moving at a relatively high speed. Dr. Finch's[3] studies of high-speed taxiway exit design have resulted in the concept of a closely spaced row of signal lights running for a short distance parallel to the runway centerline and then turning off into the taxiway.

Several kinds of luminaires, ranging from open grid lights to one-inch-high prism lights, have been designed to fill the needs of a narrow gage lighting system. These have had various degrees of success, having advantages and disadvantages. Without going into the pros and cons of these luminaires, let us instead review the design requirements of a signal light which can be used in the three types of service described above.

First, let us consider the optical requirements. In order for the light to be useful, it must direct light toward a pilot who is anywhere on the runway or in a position above it such that he is about to execute a landing. Some geometrical calculations will readily disclose the limits of beam spread. For example, assume a pilot in a modern fighter aircraft just touching down on the runway. His head is about 9 feet above the runway and when looking at a light 1000 feet ahead, his line of vision makes an angle with the ground level of about ½ degree. In order for the pilot to see lights beyond that (and 1000 feet is covered in only a few seconds by modern aircraft) part of the beam must emerge at angles even closer to the ground. The structure of the cockpit and the nose of the plane determine the top cutoff of the beam. The aircraft cockpit permits the average pilot to see only about 15 degrees below the horizon at most, and this only if the plane is not in a nose-up attitude. Thus, any light emerging from the signal light above about 15 degrees from ground level can only shine over the pilot's head because of the plane's interference. Such light at higher angles would only momentarily illuminate the ceiling over the pilot's head as he moves across the light.

The required lateral spread would be governed by how far laterally displaced a plane may be and still need useful guidance from a light. The extreme condition here would be with the pilot at the edge of the runway in relation to the centerline lights. In such a case, he would be laterally displaced a maximum of approximately 80 feet. He would be approximately 12 degrees off the axis of a light 400 feet head, and closer to the axis of any more distant light.

Therefore, the beam limits are defined as from ground level (0 degrees) to a maximum of 15 degrees vertical, and a total lateral spread of 24 degrees.

The candlepower requirements are dictated by the necessity of maintaining a minimum 400-foot forward visibility in a 700-foot runway visual range, as suggested in the proposed National Standards for runway touchdown zones, centerlines, and high-speed taxiway exit lighting. By Allard's Law, approximately 350 candlepower is needed to have a forward visibility of ⅛ mile in ⅛-mile runway visual range. This is almost twice the proposed minimum forward visibility. This candlepower is needed as close to the runway surface as possible. Such relatively high candlepowers to satisfy minimum visual conditions will be too high for good weather conditions and, therefore, use of the standard brightness controls will be necessary for these lights.

It has been proposed that the high-speed taxiway turn-off lights be further identified by making them some distinct color. As such, provisions for a color filter must be provided in the light.

Let us now take a look at the mechanical considerations of such a signal light. The most important consideration is that such a light must lend itself to relatively simple and inexpensive installation in existing runway pavement as well as in new runways. For, after all, if these new lighting concepts cannot be adapted to present runways without tearing them up and completely rebuilding them, the expense and time to adapt them will be prohibitive. Therefore, a light that mounts in a shallow recess in the pavement will be best. Modern diamond drills and saws can then be used to make recesses for the lights and cut shallow slots in the pavement for the wires.

Any such light must withstand the loads that may be imposed on it by aircraft and other vehicles. This includes dynamic as well as static loads. Modern aircraft tires carry tire pressure of 300 psi. The maximum internal tire pressure presently contemplated is 625 psi. The light must be able to take such a load.

Further consideration of load carrying problems soon points up some other important criteria. The capacity to carry a static load of 625 psi is one thing, whereas the ability to withstand the impact load of a not yet rotating tire just before touch

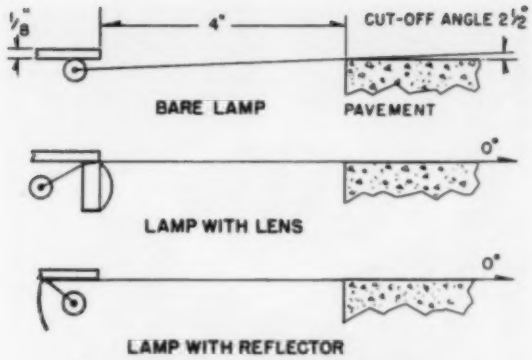

Figure 1. Comparison of optical systems.

down is a very different condition. The protrusion of the light above the pavement needs to be considered. Obviously, a light completely flush with the pavement will be less susceptible to impacts from moving objects, whereas one that protrudes one or more inches will be more susceptible to damage and more likely to damage the aircraft. The effect on other types of vehicles and objects must also be considered. For instance, the light must not deter snowplow equipment operations. This means that it should have gradually sloped edges so that a snowplow blade can ride up and over the light without damage. Also, any recesses in the light should have gradually sloped sides so that the blade shoes or dolly wheels will not be snared by the light. Another unsuspected hazard to the light, on military field at least ,is that of tailhooks. These are a minimum of 1½ inches wide and give another reason for making any recesses narrow, with sloping sides.

The light must also lend itself to easy maintenance. Relamping time should be kept to a minimum because there are many runways that cannot be shut down for lengthy periods. This same reasoning applies to periodic cleaning.

Let us also look at the electrical requirements of such a light. Transformers must be used to connect these lights with the rest of the airport lighting. A transformer at the light location requires more space in the runway and requires running the high-voltage primaries of the transformer out into the runway. A more practical arrangement from the standpoints of transformer servicing and electrical safety would be to mount the transformers at the edge of the runway and carry the low-voltage secondaries out to the lights in the runway.

Further, the lights must be operable under all weather extremes, including combinations of rain, snow, wind, heat, and cold. Being in the runway and partly recessed, it is conceivable that the light will sometimes have to operate while completely submerged or icebound. If it is in an arid desert region, it must withstand high heat. The exhaust from jet engines probably represents the highest velocities of wind that may be encountered, but remember that these are tremendously hot as well.

Probably the most important consideration of a design solution to the above mentioned criteria is that of choice of a light source. The compactness and high lumen maintenance throughout life of the 45-watt quartz iodine-cycle lamp, reported at the 1959 IES Convention in San Francisco,[4] lends itself very well to the design of a compact signal light.

Since the optical requirements of a sizable illuminated source above the pavement work directly against the safety requirements of minimum protrusion, a compromise is obviously necessary. A review of runway construction and maintenance shows that caulking for expansion joints has a per-

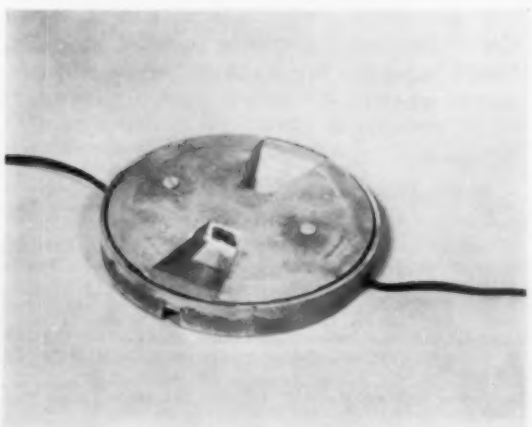

Figure 2. A bidirectional 45-watt inset light.

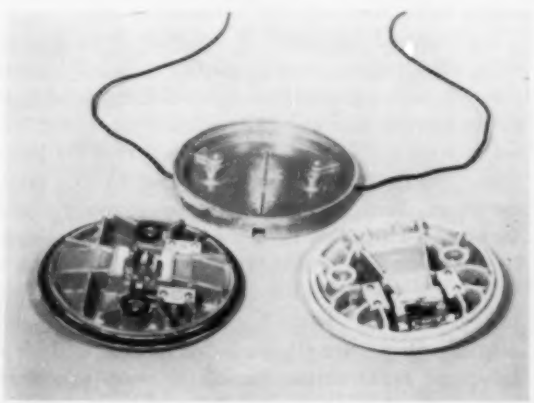

Figure 3. An inset light receptacle with bidirectional (left) and unidirectional (right) top assemblies.

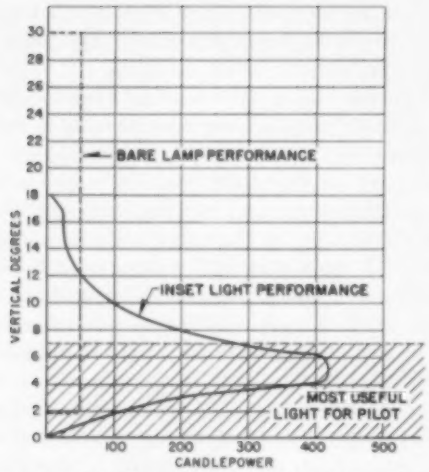

Figure 4. Typical performance of a bidirectional 45-watt inset light.

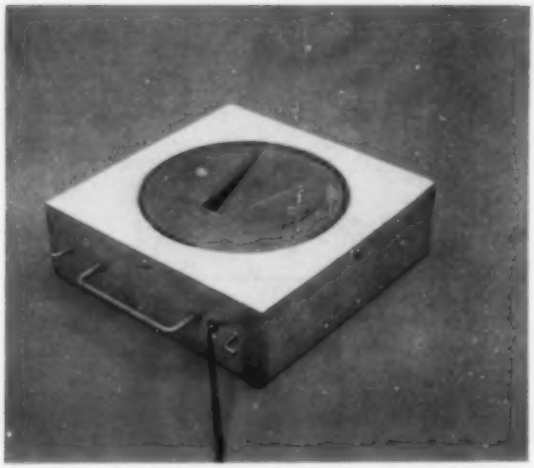

Figure 5. A unidirectional 45-watt inset light as it would appear when installed in pavement.

missible height of ⅛ inch and has not proven detrimental to aircraft operations or equipment. Let this ⅛ inch be the maximum limit of the protrusion of the light above the runway.

A choice of optical system is the next most important consideration. Several possibilities of forming the beam exist: (1) bare lamp; (2) lamp with a lens; (3) lamp with a reflector; or (4) a combination of lens and reflector with the lamp. Of these, the first is limited to the candlepower that the bare lamp can produce. The latter three permit multiplication of bare-lamp candlepower and flexibility in directing and shaping the beam. With a given thickness of metal for strength over the optics, a lens or reflector will direct light at angles closer to the runway than will be possible with a bare lamp. This is shown in Fig. 1. Of the latter three, the lens lends itself particularly well toward construction of an enclosed luminaire. It can be sealed into the luminaire and serve to keep dirt and debris from accumulating around the lamp.

An enclosed luminaire is desirable from several other standpoints. In a luminaire which is almost entirely under ground, an exposed lamp would, at times, have to operate while submerged under water or with air constantly blowing across the bulb. Such operation is not recommended by the lamp designers. With a sealed luminaire, it is not necessary to seal the electrical connections to the lamp itself. Therefore, a standard lamp may be used.

The final design of a luminaire which satisfies the design requirements is an 8-inch diameter light, 1⅛ inch thick over-all, as shown in Fig. 2. It is a two-piece construction having a receptacle with wire leads which is permanently cemented into the runway pavement, and a top assembly which mounts in the receptacle and contains the lamp, lens, mounting bolts, electrical contacts, color filter (if used) and gaskets. Two top assemblies were developed—one a unidirectional light, and the other a bidirectional light. Either will mount on the receptacle. Both top assemblies and a receptacle are shown in Fig. 3.

Typical photometric performance is shown in Fig. 4. The curve is a vertical candlepower trace through the lateral beam axis. The beam is rectangularly shaped, approximately 26 degrees wide, with rounded corners.

The luminaire described here is a result of an attempt to provide the best possible luminaire to meet the operational requirements and criteria mentioned earlier. Fig. 5 shows the unidirectional luminaire as it would appear when mounted in pavement. Undoubtedly, more improvements will be made. These may take the course of using higher-wattage lamps or of using improved optics in the luminaire to improve performance at low angles. These lights are being installed on several United States Air Force and civilian fields throughout the country.

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DISCUSSION

W. C. Fisher:* The Federal Aviation Agency has tested a number of configurations of narrow gage lighting and finds it important to have centerline lights the entire length of the narrow gage lighting. We recently tested five different systems. The system which rated first was a narrow gage with centerline and the system which rated last was identical, except that the centerline did not start until the end of the narrow gage lighting. We feel, therefore, that the most important aspect of the runway lighting is the centerline of lights. At present, we are testing several additional configurations in order to determine whether these represent improvements over the narrow gage and centerline configuration.

While the optical requirements given may be theoretically correct on the basis of the assumptions made, there are a number of factors which might very well cause a different set of requirements. Some examples of these factors are as follows:

(a) Since the pilot is normally at about 50 feet above the pavement when he crosses the threshold, it is most desirable for the vertical beam spread to be at least 20 degrees above the horizontal.

(b) It is not considered practicable to hold installation tolerances to more than ± 1/16 inch, in order to allow low cost installations. This further increases the required vertical and horizontal spread of the light.

Except for certain rare daylight low-visibility conditions, the tests conducted at the National Aviation Facilities Experimental Center have shown that the bare lamp 45-watt pancake light will meet all intensity requirements for centerline lights. The test facility states that each narrow gage light requires a minimum of 15,000 candlepower; published results of these tests should be available soon.

The Federal Aviation Agency, in its experimental pancake light specifications, has required a maximum protrusion of ¼ inch, since the ⅛-inch requirement excessively limits the possible light output. Even the design shown in this paper suffers a considerable candlepower reduction below 2 degrees. By allowing ¼-inch protrusion we can get full output down to about ½ degree with the 45-watt lamp and to about 1 degree with the 100-watt lamp.

One of the major objections to an enclosed luminaire is the problem of keeping moisture out of the light. Moisture inside the light causes problems with contacts and other materials. A second objection to the enclosed luminaire is the cost of this type of unit, which is inherently more expensive than the open type.

R. L. Paugh:** The author mentions that operation of the 45-watt quartz iodine-cycle lamp while it is submerged under water or while air is constantly blowing across the bulb is not recommended by the lamp designers. I feel this point needs clarification.

The statement is true providing the conditions cited reduce the bulb temperature of this lamp below 250°C when the lamp is operated at rated current. This will produce bulb wall blackening, since the iodine cycle will not operate, resulting in a poor lamp maintenance characteristic. However, if the lamp is operated at reduced bulb wall temperature for a relatively short time, compared to the time the lamp is burned with normal bulb temperature, there is no apparent change in lamp maintenance since the iodine cycle, when operating, not only prevents bulb wall blackening, but will remove bulb wall blackening resulting from the operation of the lamp at bulb wall temperatures which are below 250°C.

T. M. Lemons:* From the title of this paper we find we are talking about "inset" runway lights, a term used by the Air Force. The Federal Aviation Agency uses the term "button" light and its design requirements differ from those of the Air Force. Since the luminaire described by Mr. Loch does not meet the specifications of the Federal Aviation Agency, I assume that he is dealing only with the Air Force requirements.

This points up a dilemma faced by all luminaire manufacturers. Talks with research and development personnel of the F. A. A. or Air Force indicate that "button" or "inset" lights are top priority items. The F. A. A. is using the National Aviation Facilities Experimental Center to evaluate all aspects of its requirements in order to arrive at a final system design. The Air Force, however, is not using a test center to evaluate its requirements. Its system is based on good engineering principles, but it might be too strict or subject to flaws.

Mr. Loch states that for ⅛ mile forward visibility 350 candlepower is a requirement for this signal system. In the case of a centerline lighting system, the Air Force has established a 20-foot spacing of luminaire criterin. Therefore, many of these lights are in the pilot's field of view. What consideration has been given to the additive effect at the candlepower from several luminaires to arrive at the candlepower design criteria for a single luminaire?

Fig. 4 shows the candlepower performance of the "inset" luminaire. Is it not possible that high candlepower in the four-to-six-degree zone might produce a veiling glare, limiting or eliminating viewing lights further down the runway whose candlepower corresponds to that in the zero-to-two-degree zone?

Much time and money has been expended since this lighting concept was originated by Professor Finch. Is there a chance that in our race to catch up with the jet age, we have overshot our mark?

C. A. Douglas:** Mr. Loch's comments regarding the very small angles of elevation at which the more distant lights are viewed when the aircraft is on the runway, and the ineffectiveness of the light which is directed at angles of elevation larger than 15 degrees, are particularly pertinent. However, he understates the requirement for light at low angles when he states that part of the beam must emerge at angles of one-half degree and less. For maximum effectiveness the intensity of these angles should be equal, or very nearly equal, to the peak intensity.

In computing the visual range of a 350-candlepower light as ⅛ mile when the runway visual range is ⅛ mile, the author has, quite understandably, confused the terms "runway visual range" and "runway visibility." Runway visual range is the distance the average pilot is expected to see high intensity runway lights. It is computed from transmissometer measurements assuming an intensity of 10,000 candelas for the runway lights. If the intensity of a light is less than 10,000 candelas the light will, of course, be

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visible for a distance which is less than the runway visual range.

Runway visibility is also determined from transmissometer measurements, but it is the distance a meteorological observer is expected to see black objects by day and low intensity lights, of the order of 25 candelas, by night. Because of the differences between pilots' thresholds and observers' thresholds, runway lights must have an intensity in the range of 300 to 500 candelas for the visual range of the runway light to be ⅛ mile when the runway visibility is ¼ mile. The intensity of the light developed by Mr. Loch is within this range when the angle of view is between four and six degrees above the horizontal. However, when the pilot eye height is nine feet, a light ⅛ mile ahead is viewed at an angle of less than 0.8 degree above the horizontal. At this angle of view the intensity of the light is about 40 candelas. Hence the distance the light can be seen is considerably less than the ¼ mile runway visibility when the light is viewed from a fighter aircraft which is on the ground.

The intensity required to meet the requirements of the proposed National Standard (400-foot visibility distance when the runway visual range is 700 feet) is of the order of 250 candelas by day and 15 candelas by night. If a pilot eye height of nine feet is assumed, the angle of view is 1.3 degrees above the horizontal. At this angle of view the present light has an intensity of about 70 candelas. Consequently, it satisfies the requirements by night but not by day.

Despite the results of my computations, I consider the design of this light a long step forward. The failure to meet the requirements of the proposed National Standard by day is primarily the result of restricting the projection of the light to ⅛ inch above the runway surface, not to deficiencies in design.

In closing, I would like to emphasize two points brought out in this discussion:

(a) Computations of the visual range of a light must be based upon the intensity in the direction at which the light is viewed when at maximum range, not necessarily on the peak intensity.

(b) Those concerned with airport operations and design must be made aware of the penalties in performance which result from restricting inset runway lights to very low heights and of the increases in performance and effectiveness which result from very small increases in height.

C. H. Loch:* In regard to Mr. Fisher's comments on the cost of enclosed inset-type lights, I would like to point out that any cost analysis should be of maintained costs, including the first costs of installation, and replacement part costs. The higher initial cost of an enclosed light will be offset by the use of a less expensive replacement lamp element.

As to the matter of protrusion, I can only reiterate that for a given fractional inch of protrusion, the use of optics will provide more low-angle light.

I thank Mr. Paugh for his clarification of the lamp operating conditions. It should be noted, however, that an exposed lamp is more likely to be subjected to low-temperature extremes, and its use will be limited in circuits having brightness control.

In answer to Mr. Lemon's question, this light was designed to meet Air Force criteria. The differences in requirements of military and government specifications is indeed a dilemma for the manufacturers, and has been for some time. The Air Force does, however, consider the results of tests made by the F.A.A., and will follow F.A.A. requirements unless they adversely affect conditions peculiar to military operations.

I want to thank Mr. Douglas for his clarification of the terms "runway visibility" and "runway visual range." His discussion of the requirements of peak candlepower at even lower angles is important and I agree that this is the direction in which future improvements must be made.

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*Author.